A FUTURE-BASED RISK ASSESSMENT
FOR THE SURVIVABILITY OF
LONG RANGE STRIKE SYSTEMS

THESIS

William D. Heuck, Jr., Major, USAF

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DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY

AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

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William D. Heuck, Jr.

Major, USAF

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William D. Heuck, Jr.
Major, USAF

Approved:

______________________________ ____________

Gary W. Kinney, Maj, USAF (Advisor) date
Assistant Professor of Operations Research
Department of Operational Sciences

______________________________ ____________

Alfred E. Thal, Jr., PhD (Reader) date
Assistant Professor of Engineering Management
Department of Systems and Engineering Management

AFIT/GRD/ENS/07-01

Abstract

The United States Air Force today faces the challenge of allocating development resources to prepare for future force projection requirements. In particular, the Air Force's core competency of Global Attack implies a future capability that can quickly and successfully deliver combat effects anywhere in the world with impunity. Understanding that the future threat environment is dynamic and that continued advancements by adversaries will likely degrade the technical superiority of today's weapon systems, the need arises for a planning model to direct development funding to areas with the greatest probability of successfully defending the strike vehicle of 2035. Examining this problem posed two distinct challenges. The first was to determine the most likely course of Integrated Air Defense System technology through the time period of interest--allowing for plausible disruptive technologies that generate orders-of-magnitude improvement in capability or even change the nature of air defense systems. The second challenge was to characterize future adversaries--requiring a broad look at political and economic trends as presented in *AF 2025*, *SPACECAST 2020* and other relevant future studies. Based on these studies, threat scenarios were generated from technical assessments of emerging technologies and evaluated using the Risk Filtering, Ranking and Management (RFRM) technique (Haimes, 2004) to explore the most severe threats to a future global strike air vehicle. The application of RFRM to the problem created a coherent threat hierarchy that enables the decision maker to examine anticipated hostile systems that may counter key U.S. strengths of stealth, speed, and high altitude

operations. Those threat scenarios were then evaluated using decision trees and sensitivity analysis to demonstrate how quantitative tools can be applied to a largely qualitative problem. Finally, this research produced an unclassified model of plausible scenarios and a variable analysis tool that is useful today, but could also be enhanced by the application of current intelligence data and updated technology projections in the future.

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The United States Air Force: For providing the education and opportunities of AFIT

William D. Heuck, Jr., Major, USAF

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A FUTURE-BASED RISK ASSESSMENT FOR THE SURVIVABILITY OF LONG RANGE STRIKE SYSTEMS

1. Introduction

1.1. Background

The Air Force is facing the challenge of determining how to best allocate budgetary and manpower resources to prepare for the needs of future Air Force "force projection" capabilities. In particular, the Air Force's core competency of Global Attack implies a future strike capability that can quickly and successfully deliver combat effects anywhere in the world with impunity. To that end the Air Force Research Lab (AFRL), Air Vehicles Directorate, is investigating a wide range of potential Long Range Strike options for the United States Air Force (USAF). The first phase of the AFRL project is to explore a mix of systems and subsystems in the context of several developed threat scenarios that are expected for the 2025 time frame and beyond. Understanding that the threat environment is dynamic and that new/emerging technologies may degrade/negate current areas of US superiority, it is important to develop a model to direct research and development funding to areas with the greatest probability of successfully employing US strike capability in the future. The purpose of this research then is to develop a future decision model that will illuminate the most likely future mission and threat scenarios, characterize probable future threats to likely system vulnerabilities, and guide the decision makers to select the most useful technologies to pursue.

1.2. Problem Statement

The Air Force is already investing personnel and financial resources to develop tomorrow's weapon systems to defend the United States against tomorrow's adversaries.

Without a clear development strategy to guide those efforts, the ability of the US to achieve a truly effective global strike capability will be significantly diminished.

This problem poses two distinct challenges. The first is to determine the most likely course of technology and its likely destination in the 2025 time period. It is not enough to make predictions based on historical data, but analyst must also allow for unexpected, disruptive technologies that generate orders-of-magnitude improvement in capability or even change the very nature of modern warfare. The second challenge is to characterize the mostly likely adversaries in the 2025 future. This requires a much broader look at the political and economic trends in the world to determine future environments. Will the US still drive the world agenda, or will several peers (or near peers) arise to present a political, economic or military challenge? Will large scale wars be prevalent or will regional conflicts, and counter terrorism likely be more common? Whatever the future holds, the geography and technology at the disposal of our adversaries will largely impact our Research and Development (R&D) choices. For example, if our most likely adversaries are expected to possess the capability to field advanced Integrated Air Defense Systems (IADs) then thought must be given to advanced countermeasures to protect the strike vehicle. On the other hand, if our most likely adversaries lack indigenous technical expertise to field IADs, then they might purchase air defense capability from the commercial market. Such purchases, if acquired and employed in piecemeal fashion (e.g., Man Portable Air Defense Systems) may not significantly threaten US global strike vehicles. Force planners would then be allowed to rely on incremental improvements to our current foundation technologies: namely vehicles that typically operate at speeds, altitudes and stealth levels beyond the reach of today's best IADs.

The main areas of concern for the developers at AFRL are those capabilities that may advance to the point that they nullify, or seriously challenge, the traditional US strike vehicle advantages of range, speed and stealth. These same advantages also tend to limit the use of escorts on many missions, so a future system would have to defend itself against evolved enemy defenses. Of particular concern for understanding and modeling future threats are the following:

1. Improved Integrated Air Defense System (IADS) detection and tracking capabilities are becoming available worldwide.
2. Advanced threat missiles with multispectral/imaging seekers are being developed.
3. High energy lasers are quickly becoming credible weapons.
4. On board missile seekers are evolving wider off-axis lock capability.
5. Surface-to-Air Missiles are increasing in their range, speed, maneuverability, and maximum altitude.

The challenge then is to explore likely future threat scenarios to help decision makers determine where to focus development efforts for countermeasures. What technologies will threaten the US strengths in the air, and how can the US mitigate the threats through the design of an integrated strike vehicle self-defense system?

1.3. Problem Approach

The problem with "predicting" the future is that, in an environment with I mperfect information, the future is inherently unpredictable with any accuracy over long periods of time. There are simply too many variables and uncertainties to generate a conclusive result. But it is possible to reasonably posit boundaries of a planning space in which to predict multiple likely futures, given clear assumptions and a rigorous methodology, and then to actively work to bring about the most favorable of the likely alternative futures.

To develop those threat scenarios, this research will use the structure of the Risk Filtering, Ranking and Management (RFRM) technique (Haimes, 2004) to explore the most severe threats and vulnerabilities to future Air Force global strike systems. The complete application of RFRM to this problem will involve examining threats from the perspective of technical capabilities of current and anticipated hostile forces that may counter key capabilities (e.g., stealth, hypersonic speed, etc) expected to be US strengths in 2025. Vulnerabilities will be examined from the perspective of all points in the kill chain to determine the unrealized weaknesses of the anticipated capabilities (e.g., radar that detects stealth aircraft). Additionally, since the scenarios are of limited use if not put in a relevant context with realistic projections, this study will explore the scenarios within the frame work of several alternative futures.

Of particular use to this effort is the *Air Force 2025 Project* (Parnell, 1997). This study constructed a value hierarchy for Air Force weapon systems that was presented in the context of six possible futures. Nine years later, it is reasonable to believe that strategic documents and facts used for creating the alternative futures may have become more coherent since the US has been through two full Quadrennial Defense Reviews, suffered a violent attack on the Homeland (9-11), executed two major combat operations (Afghanistan and Iraq), and are currently engaged in a global war on terror. There are also now other examples of military-relevant alternative futures studies to compare with the Air Force 2025 model.

In addition, it will be necessary to examine techniques for projecting the advance of current technologies and allowing for the insertion of disruptive technologies as part of the development of future threat scenarios. Since this research is structured to provide a methodology, not generate an in depth analysis of technologies, it will require an authoritative starting point and guidelines to project future technology threats. Of particularly use in this area is the National Research Council's report on *Avoiding Surprise in an Era of Global Technology Advances* (NRC, 2005). Not only does their report help to establish an expert vision of relevant technologies (based on CIA estimates), but it looks specifically at threats to US airpower in an urban environment. Using this document (and others) as a foundation will help to create realistic risk scenarios with credible likelihood and consequent variables.

1.4. Research Scope

AFRL is tasked with developing an integrated defensive suite that will maximize vehicle survivability in a high-threat environment of the future (approximately 2025-2035). According to the Air Vehicles Directorate's project briefing, the first phase of the development effort is meant to characterize future threats and create simulations for planning. It is a multi-agency integrated effort that will leverage on-going and upcoming technology development efforts to 1) collect or generate future mission and threat scenarios, 2) identify system functional requirements based on future scenarios, 3) collect or produce data to characterize future threat system vulnerabilities and defensive system capabilities, 4) characterize and evaluate alternative technology solutions for each component of the defensive system, 5) perform system-level parametric trade studies to identify high pay-off solutions, 6) provide guidance for future technology development, and 7) to develop and utilize the simulation environment to demonstrate integrated capabilities. Additional program phases will follow, that will lead to advanced modeling, prototyping and fielding of an operational system.

In support of the Phase I effort, this research will seek to develop a credible, scenario-based model to help decision makers devise an R&D strategy to counter the most likely future threats to a global strike platform. The goal is to make the model easily adjustable (using MS Excel software) so critical values can be modified as more detailed/reliable information becomes available over time.

1.5. Outline

Chapter 2 reviews the relevant literature in the area of future prediction, technology trends, use of scenarios for decision making, and introduces the RFRM process. In Chapter 3, RFRM is used to develop decision-making scenarios, and establish the future decision space. Chapter 4 applies the methodology to match likely future threats to R&D of key technologies to counter those threats. Finally, Chapter 5 reviews the conclusions and recommendations drawn from the Chapter 4 analysis.

2. Literature Review

2.1. Using Scenarios for Decision Analysis

While not in abundance, there are relevant examples of using future projections, along with decision analysis techniques, to help guide decision makers with strategic planning. However, past efforts, specifically with military objectives, are quite few.

The *SPACECAST 2020* and *AIR FORCE 2025* teams focused their efforts generating future mission concepts and creating ideas for innovative technological solutions. They then used sensitivity analysis to help the decision maker determine the most robust options that would be useful across a broad spectrum of future realities. Both efforts enlisted the aid of Department of Defense (DoD) subject matter experts to create lists of possible future technologies (Parnell 1997, 1999) then attempted to lay them in against future scenarios.

One of the greatest challenges with this type of uncertainty-mitigating endeavor is to define a list of outcomes that are mutually exclusive and collectively exhaustive, and then assign probabilities to each outcome (Parnell 1999). The problem with applying this kind of technique to the long-range future is that there is no way to be sure that the analyst has included all possible outcomes. Indeed, there are far too many unknowns to quantify a solid probability of any outcome. One way to address this challenge is to assess different multi-objective weights for each alternate future, then use those weights to conduct a sensitivity analysis to identify the Research & Development (R&D) concepts that have the most utility across the range of likely alternate futures (Parnell, 1999).

For both of the benchmark AF studies (*SPACECAST 2020* and *Air Force 2025*), the researchers considered the alternate futures to be synonymous with "scenarios."

However, they could have just as easily applied the analysis to individual threat scenarios in the decision space of the respective alternative futures.

2.2. Developing Future Scenarios

> *"Many people have assumed that their past experience is a fairly reliable guide to the future…However, the pace of change now makes it clear to thoughtful people that continuity can no longer be taken for granted…instead of predicting what the future will be, futurists use a wide range of methodologies to engage in structured and thoughtful speculation about future possibilities"* (Institute for Alternative Futures).

Any useful planning scenarios for the far future will need to be considered in the context of the world in the future. For example, one set of threat scenarios is likely if the world of the future has made broad economic and technological advances and supports a healthy weapons market in the context of global proliferation. Conversely, a different set of threat scenarios would be likely in a world of extreme political and economic polarization that dampened technological advancement and stifled the global economy.

While developing a new and rich selection of future worlds, or scenario spaces, is beyond the scope of this research, it is still important to put together a context for scenario development. To that end this research will investigate alternative futures already developed by reliable sources that are targeted at roughly the same time frame under investigation for the Air Force's next-generation global strike vehicle (approximately 2025-2035).

To ensure the alternative futures were developed with a sufficiently germane paradigm, preference will be given to studies done in support of military planning. Next, alternative futures derived from non-DoD studies but having an aerospace flavor will be considered. Finally, government or credible non-government studies that address technology, warfare and/or the political-economic state of the world will be considered.

Five examples stand out as being particularly useful for developing military threat scenarios in the 2020-2030 time frame. The *SPACECAST 2020* project was performed by Air University (AU) in 1994 in response to a Chief of Staff of the Air Force (CSAF) request for a systems acquisition strategy to address the future operational space systems of the Air Force (Parnell, 1994). The project goal was to forecast the most likely space-oriented worlds of the future (Parnell, 1994) and project the military systems that would be most advantageous in those worlds. The *Air Force 2025* project was performed by AU in 1997 in response to a CSAF request for a similar approach to identifying combat systems across the entire spectrum of the Air Force combat arena. In a similar effort, the National Aeronautics and Space Administration (NASA) investigated alternative futures to help generate a viable science strategy to address the future aerospace environment. More recently, the National Intelligence Council's 2020 project (NIC, 2004), *Mapping the Global Future* took a broader look at several economic deterministic indicators to create global futures. Finally, the US Army, via the RAND Corporation, conducted a futures study titled *Alternate Futures and Army Force Planning* (RAND, 2005) which continued in the military theme for alternative futures development.

All five of the development efforts tended to follow a similar methodology for devising the alternative futures. They relied on a panel of experts in various fields relevant to the study and employed several brainstorming and scenario building methods to devise the future worlds. The development also relied on extensive projections of current situations into the future to develop alternative scenarios, and (in some cases) devising a future world then "backcasting" to the present to discover a likely path.

What follows is a brief summary of each of the strategies, insofar as their alternative futures are concerned, and an analysis of the common threads to discern a useful pattern or guiding conclusions to help develop relevant threat scenarios in a future world.

2.2.1. SPACECAST 2020 (1994)

The *SPACECAST 2020* project team began by devising drivers that would shape future environments. They initially generated a list of 60 drivers, and used affinity diagrams and other team techniques to reduce the drivers to 3 inclusive categories: *Number of Actors with a Space Role, Will to Use Space, and Technomic Capability* (defined as the technological proliferation and growth and economic vitality of the actors). These three drivers were then given binary values (respectively: Many or Few, Strong or Weak, and Low or High).

This exercise produced eight alternate futures, which the team named and then culled to what they determined were the four likeliest (highlighted in Table 1): *Spacefaring*, *Mad Max Inc*., *Rogues*, and *SPACECAST* (considered by the team to be the most likely of all the scenarios).

Table 1: SPACECAST 2020 Alternative Futures

No. Actors with Space Role	Technomic Vitality	Will to Use Space	Scenario

1. Many	**High**	**Strong**	**SPACEFARING**
2. Many	High	Weak	TERRESTRIAL FOCUS
3. Many	**Low**	**Strong**	**MAD MAX, INC.**
4. Many	Low	Weak	BALKANIZED
5. Few	High	Strong	SPACE BARONS
6. Few	**High**	**Weak**	**SPACECAST**
7. Few	**Low**	**Strong**	**ROGUES**
8. Few	Low	Weak	FUNDAMENTALIST

2.2.2. AIR FORCE 2025 (1997)

The *Air Force 2025* team used a variety of scientific and non-scientific methods to develop their list of drivers, and then ultimately selected 3 variables that incorporated a wide range of drivers (much like the *SPACECAST 2020* effort). Those drivers included the following, which were each given a binary value:

American Worldview: The US perspective of the world which drives its willingness and capability to take the lead in international affairs (value settings: Domestic or Global)

ΔTeK: The ability to employ technology. It describes the rate of change in advancement and proliferation of technology (value settings: Constrained and Exponential)

World Power Grid: Describes the sources and control of political, military, economic and informational power throughout the world (value settings: Concentrated or Dispersed).

These three parameters generate eight distinct Future World Scenarios (Table 2), from which the team selected the four which seemed most applicable for planning because they exercised the extreme ranges of the chosen variables.

Table 2: Air Force 2025 Alternative Futures

World	American World View	ΔTeK	World Power Grid	Name
1	**Global**	**Exponential**	**Dispersed**	**DIGITAL CACOPHONY**
2	Global	Exponential	Concentrated	STAR TREK
3	**Global**	**Constrained**	**Dispersed**	**GULLIVER'S TRAVAILS**
4	Global	Constrained	Concentrated	PAX AMERICANA
5	Domestic	Exponential	Dispersed	BYTE!
6	**Domestic**	**Exponential**	**Concentrated**	**ZAIBATSU**
7	Domestic	Constrained	Dispersed	HOOVERVILLE
8	**Domestic**	**Constrained**	**Concentrated**	**KING KHAN**

Digital Cacophony is a world of almost unlimited technology.

Gulliver's Travails is a world of rampant nationalism, state and non-state terrorism, and fluid coalitions. America's ability to influence events is dispersed by the vast numbers of different actors.

Zaibatsu is a world where the sovereignty of the nation-state has been diminished by profit-seeking multinational corporations.

King Khan is a world dominated by a foreign (Asian) superpower. The United States has become the "United Kingdom of the Twenty-first Century."

2.2.3. NASA Study (1997)

In the NASA study, the National Research Council developed five future world scenarios. They began by establishing some basic economic, social and policy factors, then refined their models by considering the role of disruptive technologies, the key issues for aeronautics and the role NASA should take in the alternative futures. The team established four main drivers, or dimensions; each with two distinct settings.

U.S. Economic Competitiveness: U.S. share of internationally traded products and services in the world economy (value setting: Strong or Weak)

Worldwide Demand for Aeronautics Products and Services: The level of demand for aeronautics products and services related to civil, military, and access to space applications (value settings: High Growth or Low Growth)

Threats to Global Security and/or Quality of Life: Direct threats to the health and safety of people, and/or the stability and viability of governments, and their implications for the United States (value settings: High Threat or Low Threat)

Global Trend in Government Participation in Society: The tendency of governments to regulate and/or intervene in key aspects of society and the economy (value settings: High or Low)

Combining the various settings for the four dimensions the team generated a total of 16 possible scenarios (Table 3). The project team then selected five of the scenarios for further analysis based on their "potential challenges or opportunities they may hold for aeronautics." Following a common practice in this type of exercise, the five alternative futures were named to give them life in the minds of the developers: *Pushing the Envelope, Grounded, Regional Tensions, Trading Places, and Environmentally Challenged.*

Table 3: NASA's Five Development Scenarios

Scenario	US Economic Competitiveness	Worldwide Demand for Aeronautics Products and Services	Threats to Global Security and/or Quality of Life	Global Trend in Government Participation in Society
PUSHING THE ENVELOPE	Strong	High Growth	Low	Low
GROUNDED	Strong	Low Growth	High	High
REGIONAL TENSIONS	Weak	High Growth	High	High
TRADING SPACES	Weak	High Growth	Low	Low
ENVIRONMENTALLY CHALLENGED	Weak	Low Growth	High	High

2.2.4. National Intelligence Council (NIC) 2020 Project (2004)

The NIC team, like the others, first conducted workshops and brainstorming sessions with a broad range of experts to develop alternative futures scenarios. However, this project was conducted over a much longer time period (more than a year as opposed to a few months) and involved a broader range of experts and topics than in the other studies. Admittedly, this "broadness" may seem to make the futures they developed less applicable to the military environment, but the extensive development process and rich future scenarios actually appear, in some ways, to be even more relevant than the more focused studies in exploring likely US adversaries. The fact that this study was completed in 2004 (as opposed to the mid/late 1990s for the more focused air and space projects) also lends contemporary relevance to the conclusions.

Davos World: Robust economic growth through 2019 reshapes the globalization process into a more non-western dynamic. The "Asian giants" as well as other developing states continue to outpace most "Western" economies. Western powers must contend with job insecurity despite the many benefits from an expanding global economy. In spite of energy profits, the Middle East lags behind and threatens the future of globalization.

Pax Americana: US dominance survives changes to the global political landscape. Relationships with Europe and Asia evolve but retain a similar dynamic to today. The United States still does the "heavy lifting" but has to struggle to "assert leadership in an increasingly diverse, complex, and fast-paced world."

A New Caliphate: Genesis of an emerging global movement fueled by radical religious identity. A new Caliphate is proclaimed and manages to advance a powerful counter ideology that has widespread appeal. It is fueled by the popularized struggles of the new Caliph as he attempts to wrest control from traditional regimes. This situation generates conflict and confusion within the Muslim world and outside between Muslims and the United States, Europe, Russia and China.

Cycle of Fear: Concerns over proliferation have increased to the point that nations have taken large scale intrusive security measures. Proliferators find it increasingly hard to operate, but with the spread of Weapons of Mass Destruction (WMD), more countries want to arm themselves for their own protection. The draconian measures increasingly implemented by governments to stem proliferation and guard against terrorism may have deleterious effects on globalization.

2.2.5. Army 2025 (2005)

The US Army commissioned a RAND study to focus on the 2025 timeframe to help determine future force makeup. The RAND team also began by defining key drivers: *Geopolitics, Economics, Demographics, Technology* and the *Environment*. Where the RAND study differed from the others under review was in the application of the variables. Instead of assigning binary values, they projected three slopes for each variable: Good (positive for US interests), Medium (neutral for US interests) and Bad (negative for US interests). Combining these variables in a 5x3 matrix generated 15 alternative futures (Table 4, below) that covered the entire spectrum of possible futures (Figure 1, below). The team then named each future and, through selection and merging, ended up with the 6 most likely alternative futures:

U.S. Unipolarity: The United States remains the world's dominant power. The other great powers (in the team's view: China, Russia, the European Union, and India) are unable and unwilling to challenge the U.S.-led international order. The US will still face threats from rogue regional and from scattered ethnic conflicts and humanitarian disasters in the poorest parts of the developing world.

Table 4: Army 2025 Alternative Futures Matrix

	Good	Medium	Bad
Demographics	Population stability	Regional overpopulation	Systemic demographic pressure
Geopolitics	Hegemonic stability or benign multipolarity	Peer competition or multipolarity	Nation-state collapse
Economics	Steady growth/ low inflation	Slowdown	Stagnation
Environment	Resource management	Water scarcity, soil erosion	Climate change, famines
Technology	Information technology boom, biotech growth	Information technology slowdown	Destructive applications

Democratic Peace: Liberal democracy and free, open markets have spread to such an extent that they are becoming institutionalized in all of the world's great powers (Europe, India, China, Japan, Russia, Brazil) as well as most middle-ranking powers. Spreading democracy has virtually eliminated the phenomenon of "rogue regional states", so proliferation of weapons of mass destruction (WMD) is not a major security issue. The key zones of instability in the Democratic Peace world are northern Latin America, Sub-Saharan Africa, and parts of South Asia.

Major Competitor Rising: A near-peer competitor to the United States emerges with significant conventional and strategic nuclear capabilities that include a power projection force and dedicated military space assets. Specifically, a Sino-Russian Entente forms in 2015–2018 with the goal of weakening America's global position as well as that of its key allies.

Competitive Multi-polarity: Two large powers emerge that are capable of challenging the United States on roughly equal terms. Each of these three powers would build its own coalition at the expense of the other two. Conflict would take the form of an ongoing competition between fluid defensive alliances that treat small powers as pawns in the larger game. The United States, Russia, and China each lead a major alliance system.

Transnational Web: The nation-state has lost a substantial amount of power to transnational actors (global corporations, criminal organizations, and terrorist networks) many of whom use the burgeoning Internet to coordinate their actions worldwide much more rapidly than can any national government bureaucracy. Also envisioned is a dramatic growth in the threat to the United States posed by radical transnational "peace and social justice" groups, which identify the United States as an "arch-villain" standing in the way of their drive to reshape the global order.

Chaos/Anarchy: Overpopulation, environmental degradation, and ethnic strife cause the collapse of the nation-state in large swaths of the developing world. The power vacuum is filled by warlords who, lacking a tax base, turn to terrorism and the smuggling of contraband, narcotics, and weapons of mass destruction to support their regimes.

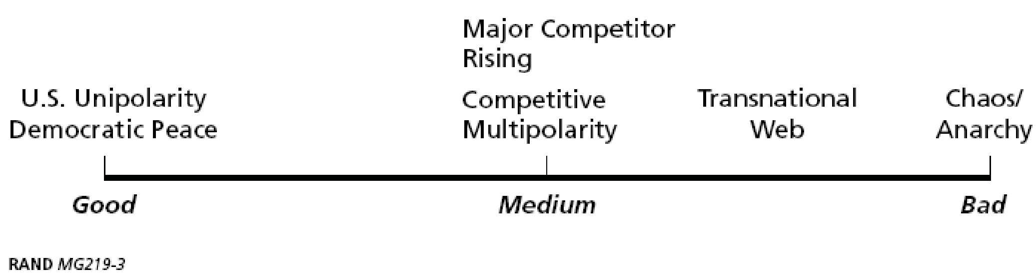

Figure 1: Army 2025 Alternative Futures Continuum

2.2.6. Synthesis

One of the goals of alternative futures, at least in the business models, is to choose the most desirable one and work to bring it about. This type of approach is especially useful for the aerospace industry study. However, in the case of the military studies, the goal is not necessarily to work toward, or bring about any particular future. Instead, the goal is to direct technology development to adequately cover all likely mission needs of anticipated in the future (within technical and economic constraints). Conversely, the goal of this study is to presage the likely capabilities of likely adversaries so research efforts can be directed to countering those capabilities which may degrade U.S. airpower advantages. To that end, there are two archetypes of adversary that would pose different challenges for engagement by a global, military strike capability: State Actor and Non-State Actor.

The five alternative-futures studies reviewed for this research do share some common threads that manifest as useful patterns. For example, *Mad Max Inc*. (*Spacecast 2020*), *Zaibatsu* (*AF 2025*,) and *Grounded* (*NASA*) all posit a future world where multinational corporations have degraded the power of the nation state and drive a global market of an increasing number of well equipped and financially robust actors. Similarly, *Gulliver's Travails* (*AF 2025*), *Pax Americana* (*NIC 2020*), and *Democratic Peace* (*Army 2025*) all envision a world that, while at relative peace due to the influence of strong hegemonic powers, is bubbling with unrest as multiple, low-intensity conflicts must be policed. Table 5 shows a comparison of the five future studies.

Table 5: Comparison of Multiple Alternative Future Predictions

SPACECAST 2020	AIR FORCE 2025	NASA	NIC 2020	ARMY 2025
Date: 1994	Date: 1996	Date: 1997	Date: 2004	Date: 2005
<u>Drivers:</u> Number of Actors National Will Technomic Vitality	<u>Drivers:</u> American Worldview ΔTeK World Power Grid	<u>Drivers:</u> US Economic Competitiveness Worldwide Demand for Aero Products Threats to Global Security / Quality of Life Global Trend in Government Participation in Society	<u>Drivers:</u> Many Technology Economics	<u>Drivers</u> Geopolitics Economics Demographics Technology Environment
<u>Primary Focus:</u> Space Technology	<u>Primary Focus:</u> Airpower	<u>Primary Focus:</u> Demand for Aerospace Products	<u>Primary Focus:</u> Political Climate	<u>Primary Focus:</u> Combat Technology
SPACE FARING	GULLIVER'S TRAVAILS	PUSHING THE ENVELOPE	DAVOS WORLD	U.S. UNIPOLARITY
ROGUES	ZAIBATSU	GROUNDED	PAX AMERICANA	DEMOCRATIC PEACE
MAD MAX INC.	DIGITAL CACOPHONY	REGIONAL TENSIONS	A NEW CALIPHATE	MAJOR COMPETITOR RISING
SPACE CAST	KING KAHN	TRADING PLACES	CYCLE OF FEAR	COMPETITIVE MULTIPOLARITY
		ENVIRONMENTAL CHALLENGE		TRANSNATIONAL WEB
				CHAOS/ANARCHY

When considered through the perspective of the two adversarial types of interest (State Actors and Non-State Actors) the future world scenarios can be grouped to indicate which type of global environment they presage (Table 6, below). For example, *Spacefaring* (*Spacecast 2020*) indicates several powerful and economically sound state actors, while *Digital Cacophony* may predict a world with such advanced technology and interconnected information resources that even the least of the non-state adversaries may be capable of posing a significant challenge to our nation's sovereign options.

Table 6: Alternative future Predictions Sorted by Adversary

	SPACECAST 2020	AIR FORCE 2025	NASA	NIC 2020	ARMY 2025
Primarily posits a few powerful State Actors	Spacefaring Space Cast	King Kahn	Pushing the Envelope Trading Places Regional Tensions	DAVOS World Pax Americana	U.S. Unipolarity Democratic Peace Major Competitor Rising Competitive Multipolarity
Primarily posits powerful Non-State Actors	Rogues Mad Max Inc.	Zaibatsu Digital Cacophony Gulliver's Travails	Grounded Environmentally Challenged	A New Caliphate Cycle of Fear	Transnational Web Chaos/Anarchy

When all scenarios are considered together, it may be possible to predict the likelihood of the United States facing a particular type of adversary. Additionally, when considering the driving factors that generate the alternative future worlds, it may be feasible to predict (using a more linear approach) which entities of today (state and non-state) would be in position to take advantage of a particular world scenario.

2.3. Mapping Technology Trends

"While U.S. air dominance is unlikely to be jeopardized by symmetric means, particularly in the near term, technology trends in commercialization and globalization suggest that new types of threats may be on the horizon." (National Research Council, 2005)

Inherent in their nature, all alternative-futures studies contain within them an assumption, either implicit or explicit, of the level of technological advancement in the future. To be useful, this assumption must be based on some reasonable prediction methodology. Often, these predictions are based on historic data and follow an incremental or linear pathway to the future. Even the exponential nature of Moore's Law is based on an assumption (heretofore born out) that computer processing power will continue to double every 18 months. Consequently, "The art of predicting technological innovation is often little more than market research in mainstream scientific trends" (Land Warfare Conference, 2002). Unfortunately, as convenient as linear projections are to create, they cannot predict non-linear advancements or novel uses of a particular advancement.

A 2005 National Research Council (NRC) study established that globalization and powerful market forces, along with a relative small US investment in R&D, present a challenge to the US and require a technology warning mechanism to protect US interests. Of particular concern are potentially disruptive technologies which, "while not seen as a near term threat, are viewed as one to which the United States is most vulnerable."

Supported by a 2001 Central Intelligence Agency (CIA) technology estimate, the NRC outlined several technologies (delineated into three tiers) that may impact national security by 2015. These technologies become even more prescient when considering the 2020-2030 time period, as they will have had more time to evolve into fieldable systems. Higher tiers are more likely to have greater impact than lower tiers, so the three tiers may be also be considered to have a High, Medium and Low likelihood of coming to fruition (in a negative way to US security). A fourth category, "other technologies considered," may also be considered to have a very low likelihood of impacting US security.

First Tier: High-Impact Technologies
- Gene Therapy
- Wireless Communications
- Image Understanding
- Cloned or Tailored Organisms
- MicroElectroMechanical Systems (MEMS)
- Nanotechnology

Second Tier Technologies
- Optical Communications
- Regenerative Medicine
- Efficient Software Development
- Sensor Webs
- Advanced Materials

Third Tier: Below-Threshold Technologies
- Hypersonic/Supersonic Aircraft
- Next-Generation Space Shuttle System
- Alternative Energy
- Distributed Energy
- New-Generation Nuclear Power Plants
- Fuel Cells

Other Technologies Considered
- Brain-Machine Interfaces
- "Smart" Materials (organic and inorganic)
- Distributed-Grid-Based Processing Systems
- Performance-Enhancing Drugs
- Multilingual Voice Recognition
- Molecular Electronics
- Ubiquitous Water Generation
- High-Power Lasers
- Directed Energy (Microwave)

Figure 2: Candidate Technologies Likely to Impact National Security by 2015

In addition to general technology trends, the NRC study looked specifically at threats to US airpower in an urban environment. Those results are particularly useful to this research because built-up areas are more likely to have advanced IADs capability and are also the areas best able to make use of disruptive technologies (e.g., passive bi-static radar) when and if they become available. According to the NRC estimates, today's

U.S.-produced aircraft are assembled from parts largely made overseas, and U.S. aerospace and electronics companies have, in effect, built up aerospace research, development, and manufacturing capability in other countries by setting up overseas research organizations—albeit for legitimate economic reasons.

The report covers several key technology areas that should be of concern to the AFRL global strike project. For example analysts address the challenges to US radar stealth.

> "To negate U.S. radar stealth advantages directly requires the development of radars with different and improved characteristics. For example, the power of the radar can be increased to illuminate even small RCS targets. Changes in frequencies and radar-emanation management can also help. On an indirect basis, other sensors could be perfected that can precisely track aircraft, such as improved infrared (IR) or optical sensors. All of these require a high degree of sophistication to invent, but they can be sold to and used by relatively unsophisticated buyers with hostile intentions." (NRC, 2005)

To address these types of technology threats the NRC team established system-level performance parameters to evaluate the foundations of new technologies to determine how and to what degree they can challenge U.S. airpower. One example is their treatment of "Increased effectiveness of man-portable air defense systems (MANPADSs)." What follows is taken from the MANPADS section of the report as an example of the types of considerations explored and the depth of analysis applied to several relevant technology areas.

Increased Range and/or Reduced Signature

•*Increasing range*. Improving this characteristic would increase the threat footprint; threaten mid and high-altitude aircraft, including ISR assets; and increase the slant range so that, for example, transports that stay within an airport perimeter would be at risk from remote launch sites.

• *Low-optical-emission propulsion*. Many aircraft missile countermeasure systems use the optical emission from the missile launch to queue the defense. Thus, no signature, no warning, no defense. Extending the definition of reduced optical emission to include smoke helps to mask the launch location and thus increase the tactical utility of the missile.

Enhanced Guidance, Navigation, and/or Targeting

• *Multimode seekers*. This improved technology would reduce or eliminate the effectiveness of countermeasures or permit non-line-of-sight launches. In addition to multiple optical bands (an approach currently popular), this might include acoustic or RF cues to allow a missile launch against a target not in sight from the launch position. With sufficient range and RF seeker performance, large radar and battle management aircraft can be placed under threat.

• *Increased accuracy guidance*. The warhead size of a man-portable missile is of the order of a kilogram. Thus, it must detonate very close to a critical location to be effective. Increased guidance accuracy, along with any necessary increase in maneuverability, will improve the lethality of these small missiles, especially against large aircraft.

Enhanced Lethality

• *Autonomous launch*. With sufficiently capable sensors, automated decision making, and hardening, these small missiles can act as aerial mines, threatening any aircraft that flies within range. Remote queuing could increase the effectiveness of such systems.

• *Expanded mission capability*. By integrating relatively simple GPS guidance, laser capability for precise geolocation, and data link capability, an adversary could transform a MANPADS from a surface-to-air weapon into one that can also perform precision engagement missions in the ground-to-ground role in a wide variety of mission areas.

The NRC team then used their established methodology to evaluate the supporting technologies that would make the new threat capability possible. The methodology looks at two main indicators: Accessibility and Maturity.

Accessibility addresses the ability of an adversary to gain access to and exploit a given technology.

Level 1. Technology is available through the Internet, being a commercial off-the-shelf item; low sophistication is required to exploit it.

Level 2. The technology would require a small investment (hundreds of dollars to a few hundred thousand dollars) in facilities and/or expertise.

Level 3. The technology would require a major investment (millions to billions of dollars) in facilities and/or expertise. Level 3 would likely require a state actor.

Maturity addresses how much is known about an adversary's intentions to exploit the technology.

Futures. Create a technology roadmap and forecast; identify potential observables to aid in the tracking of technological advances.

Technology Watch. Monitor (global) communications and publications for breakthroughs and integrations.

Technology Warning. Positive observables indicate that a prototype has been achieved.

Technology Alert. An adversary has been identified and operational capability is known to exist.

Several examples of relevant technologies are addressed and help establish likelihood's and consequences of individual advancements (Table 7). From these examples, one could generate a risk matrix that would indicate the risk of technology development and employment for use in a probabilistic decision analysis technique.

Table 7: Technology Warning Assessment Matrix

Tech Item	Accessibility	Maturity	Consequence
Small Low-Cost Jet Engines	Level 2	Warning	Negate man-portable air defense system (MANPADS) launch warning; greatly extend MANPADS range; extend unmanned aerial vehicle range (to thousands of kilometers) and speed.
Storable liquid propellant, micro rocket engines	Level 3	Warning	Negate man-portable air defense system (MANPADS) launch warning; extend MANPADS range; anti-satellite interceptors; micro intercontinental ballistic missile or launch vehicles.
Higher Performance Small rocket engines	Level 3	Watch	Small intercontinental ballistic missiles and space launchers
Nanoscale surface machining	Level 2	Watch	Optical/Infrared (IR) Stealth
Electronically tuned surface coatings	Level 2	Warning	Optical/IR Stealth
Negative Index of refraction materials	Level 2	Watch	Improved infrared, optical and RF stealth
Low cost, uncooled, low noise infrared detector arrays (especially mid-wave and long-wave)	Level 2	Warning	Improved capability and range in man-portable air defense systems
Narrowband, tunable frequency agile, imaging infrared optical filters	Level 2	Warning	Improved capability, countermeasure robust man-portable air defense systems.
High-accuracy microelectromechanical systems (MEMS) gyros and accelerometers	Level 3	Warning	Very Long range small unmanned aerial vehicles, missiles and launch vehicles.
Automated, ad hoc, cellular phone/computer systems	Level 1	Alert	Remote queuing/targeting for man-portable air defense systems and mines; large, informal sensor and/or computer arrays for anti-stealth
High-speed processor chips and mega-flash memories	Level 2	Warning	Targeting and/or discrimination algorithms
Increased energy density or slow-burning energetic materials	Level 2	Watch	Extend man-portable air defense systems range; increase lethality

Tech Item	Accessibility	Maturity	Consequence
Very low cost Radio Frequency (RF) proximity fuses	Level 2	Warning	Aerial mines
Increased speed digital signal processor and processor chips	Level 3	Warning	Anti-fuse systems
Very high pulse power systems	Level 2	Warning	Non-Nuclear Electromagnetic Pulse (EMP)
Tactical Nuclear EMP	UNK	UNK	Disable AC while in flight or on the ground
Wireless technology, frequency modulation techniques, global positioning system crypto capture	Jamming: Level 1 Spoofing: level 3	Alert Watch	Improved, low-cost Global Positioning System (GPS) jammers and spoofers.
Multi-static systems	Level 2	Warning	Mitigate current RF stealth technologies

2.4. Risk Filtering Ranking and Management (RFRM)

Risk Filtering Ranking and Management (RFRM) is a method of Risk Scenario Development created by Yacov Haimes. It is a "…modified and much-improved version of Risk Ranking and Filtering developed for NASA in the early 1990s." (Haimes). It is also a specific and philosophical application of Haimes standard, 5-step risk assessment process:

1. Risk Identification
2. Risk Modeling, Quantification and Measurement
3. Risk Evaluation
4. Risk Acceptance and Avoidance
5. Risk Management

In RFRM, likelihood is used as a general estimation of the probability of a scenario occurring. The likelihood estimate is based on available evidence and assigns a probability of occurrence to each scenario (in place of the true, unknown probability of the scenario occurring). The evidence may be objective (as in the case of historical data) or subjective (subject matter expert opinion). Either type of evidence is valid but each relies on different theories for analysis. The Frequentist view says that if the scenario happens repeatedly then the question "how frequently" can be asked, and the answer can be expressed in occurrence per unit time or frequency. On other hand, the Bayesian method says that if the scenario is <u>not</u> recurrent then assignment of occurrence is subjective in the sense that it describes a state of knowledge rather than any property of the real world. However, it is objective in the sense that it should be independent of the personality of the user. Users with common knowledge, analysis ability, and expertise should assign the same probability to a particular scenario.

The 5-Step risk assessment process described by Haimes is designed to bring out the scenarios most useful to the decision maker. The first step, *Risk Identification,* answers the question "What can go wrong?" This step involves identifying risk scenarios while taking into account the sources and nature of the likely risk. Obviously, analysis of real world problems can produce hundreds or thousands of scenarios. Since it is time/resource prohibitive to perform quantitative risk analysis on all these scenarios, Haimes developed a methodology to establish priorities among a large number of scenarios to identify the most important contributors to risk. This methodology is the RFRM process.

There are eight phases to the RFRM method: *Scenario Identification, Scenario Filtering, Bicriteria Filtering and Ranking, Multicriteria Evaluation, Quantitative Ranking, Risk Management, Safeguarding against Missing Critical Items, and Operational Feedback*. Each phase is specifically designed to help hone in on the most critical areas for the decision maker's attention. To illustrate the technique, an example is provided that considers the bed down decision for an interceptor battery component of the national missile defense system (NMD).

Phase 1: Identifying Risk Scenarios through Hierarchical Holographic Modeling: Identify all "success" scenarios and all "risk" scenarios. To do this Haimes uses a technique he developed termed Hierarchical Holographic Modeling (HHM). HHM provides multiple decompositions (perspectives or views) of a given problem. Each of the decompositions has its own unique qualities, issues, limitations, and factors. The result of the HHM generation process is the creation of a number of risk scenarios, hierarchically organized into set and subsets. Identification will probably contain hundreds if not thousands of risk scenarios, but the final product will be a set of HHM diagrams and a list of risk scenarios.

For the bed down example there are four head topics (see Figure 4): Physical Infrastructure, Safety and Security, Personnel Support, and Operations and Maintenance. Based on research, experience and expert opinion, several risk scenarios were generated under each head topic. The HHM shows just the title, but each scenario must be developed and supported with real data to add value to the model. For example, under the Operations and Maintenance head topic, one risk scenario category is titled Mission

Conflict. One of the risk scenarios (there may be one or several in each category) posits that a space lift mission is in terminal countdown when an enemy launches a surprise ICBM attack. This eventuality if not properly understood and planned for could create conflicts in range assets, command and control and public safety. Technical and management details of the scenario would then be developed to the point where a decision maker could properly understand the implications and take effective action to deal with the risk.

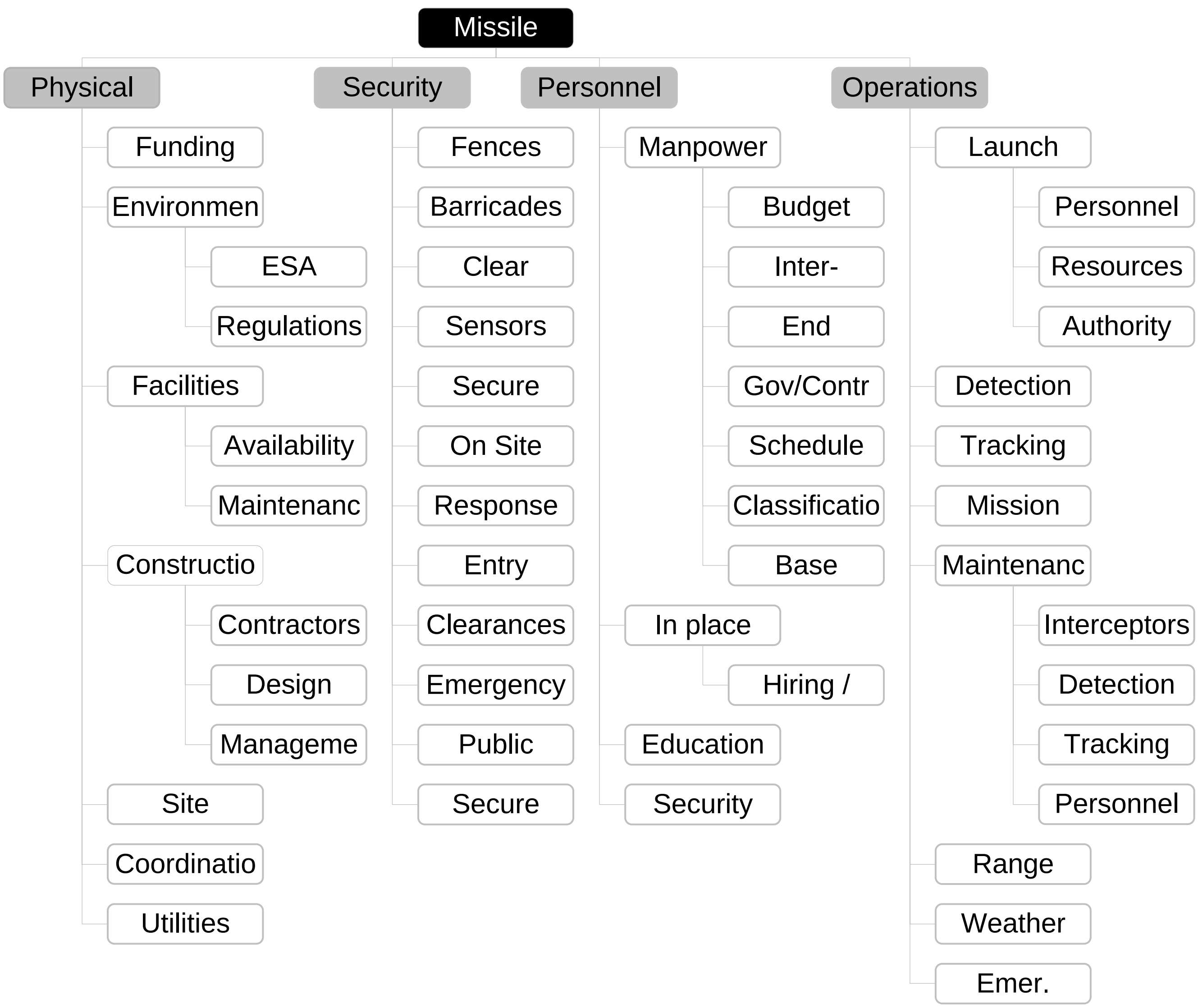

Figure 3: NMD Example--HHM

Phase 2: Scenario Filtering Based on Scope, Temporal Domain, and Level of Decision Making: The risk scenarios identified in Phase 1 are filtered (at the subtopic level) according to the responsibilities and interests of the decision maker (DM). As previously stated the number of "subtopics" may easily be in the hundreds or thousands. Therefore, not all these subtopics will be of immediate concern to the decision maker(s). Typical filtering criteria for this first look center on the decision maker's perspective and which items are of particular relevance to him/her. This selective filtering is why the single HHM could be of value to decision makers at several levels. The director of the Missile Defense Agency would filter different risks than would the chief of security forces at the bed down location. Regardless of the DM this initial filtering would ideally produce a list of no more than 50 risk scenarios. Figure 5 shows how a sample DM might remove (shaded) some risk categories from consideration.

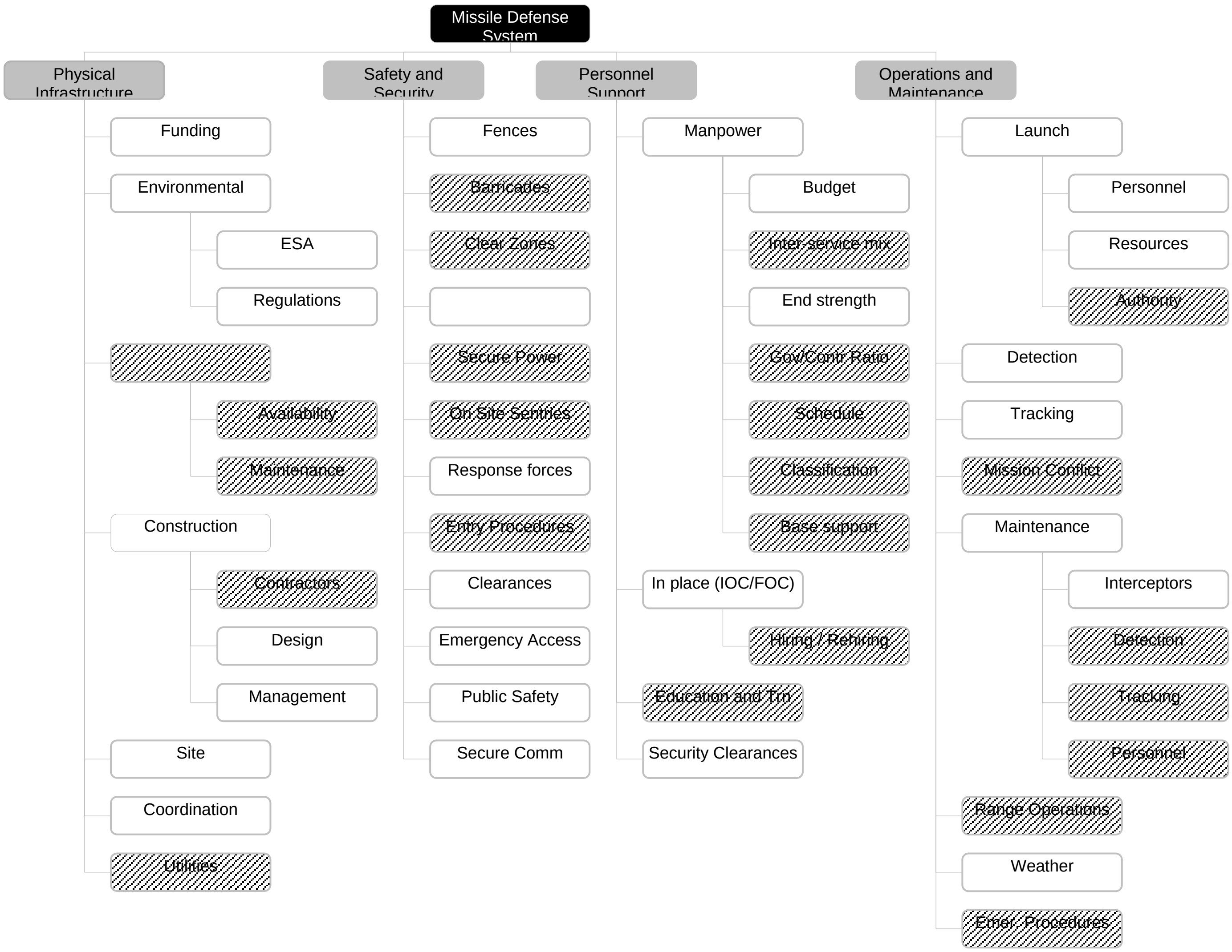

Figure 4: NMD Example--Filtered HHM

Phase 3: Bi-criteria Filtering and Ranking: The remaining risk scenarios identified in Phase 2 are further filtered by assigning a qualitative likelihood and consequence to each scenario. This process uses the ordinal version of the USAF Risk Matrix (MIL-STD 882D, US Dept of Defense, Standard Practice for System Safety). The HHM subtopics (scenario categories) are distributed to the cells of the risk matrix. Those subtopics falling in the low-risk boxes are filtered out and set aside for later consideration. This phase produces a further filtered list of "risk" scenarios. Note, that in the example Bi-criteria Matrix (Table 7) each scenario has been given an alphanumeric designator to allow easy reference to a master scenario list.

Table 8: NMD Example--Bicriteria Matrix

Effect \ Likelihood	Very Low	Low	Moderate	High	Very High
Catastrophic	S44 S59 S62	S2 S4			
Critical	S42	S7 S56	S46 S58 S49	S13 S48	
Serious				S30 S47	S38
Moderate					S16 S24
Marginal					

Low Risk	Moderate Risk	High Risk	Extremely High Risk

Phase 4: Multicriteria Evaluation: In this phase, each risk scenario is evaluated on more detailed consequence criteria. Haimes includes a list of 3 system attributes and 11 criteria. The 3 attribute categories are scored based on the ability of each risk scenario to impact the system in the areas of: *Redundancy* (Ability of extra components of a system to assume the functions of failed components), *Resiliency* (Ability of the system to recover following a failure or emergency), and *Robustness* (Insensitivity of system performance to external stresses). These 3 categories are broken down into 11 criteria for detailed evaluation (Haimes, 2004):

Undetectability refers to the absence of modes by which the initial event of a scenario can be discovered before harm occurs.

Uncontrollability refers to the absence of control modes that make it possible to take action or make an adjustment to prevent harm.

Multiple paths to failure indicates that there are multiple and possibly unknown ways for the events of a scenario to harm the system, such as circumventing safety devices, for example.

Irreversibility indicates a scenario in which the adverse condition cannot be returned to the initial, operational (pre-event) condition.

Duration of effects indicates a scenario that would have a long duration of adverse consequences.

Cascading effects indicates a scenario where the effects of an adverse condition readily propagate to the other subsystems of a system, i.e., cannot be contained.

Operating environment indicates a scenario that results from external stressors.

Wear and Tear indicates a scenario that results from use, leading to degraded performance.

HW/SW/HU/OR interfaces indicate a scenario in which the adverse outcome is magnified by interfaces among diverse subsystems (e.g., human and hardware).

Complexity/emergent behaviors indicate a scenario in which there is a potential for system-level behaviors that are not anticipated even with knowledge of the components and the laws of their interactions.

Design immaturity indicates a scenario in which the adverse consequences are related to the newness of the system design of other lack of a proven concept.

Each criterion is then scored such that a higher value indicates higher consequence. Qualitative descriptions such as “not applicable”, “low”, “medium”, or “high” can suffice in the place of a quantitative score. Haimes gives no preferred methodology for assessing the overall risk level, so the analyst must give careful consideration to the relevance and weight of each criterion for the particular scenario under consideration. A sampling of this analysis from the bed down example is in Table 9. The sample shows that scenario S13 has been filtered based on the severity of a failure relative to other scenarios.

Table 9: NMD Example--Multicriteria Filtering (Partial List)

Scenario	1	2	3	4	5	6	7	8	9	10	11
Launch	Det	Con	MPF	Irr	DoE	Casc	Op E	W&T	HSHOI	Com	DI
S2 - Adequate number of interceptors are not operational to defeat incoming ICBM threat. Results in casualties caused by ICBM detonations.	L	M	L	H	H	L	H	L	L	M	H
Detection											
S4 - Detection resources are not operational which allows enemy ICBMs to intrude US airspace without warning.	L	L	M	M	M	M	H	M	M	M	M
Maintenance											
S7 - Maintenance issues cause an increased number of interceptors to be unavailable, causing the effectiveness of the system to be decreased.	H	M	H	L	M	H	M	H	L	M	M
Weather											
S13 - Interceptor effectiveness may be reduced in certain types of weather.	M	H	M	L	L	M	M	L	L	M	L

Phase 5: Quantitative Ranking: In this phase the likelihood of each scenario is quantified based on the totality of relevant evidence available (using Bayes' theorem where necessary to process the evidence items). Calculating these quantitative likelihoods helps to avoid miscommunication when interpreting qualitative likelihoods (Phase 3) such as "unlikely", "seldom", "occasional", "likely", and "frequent." When combined with the results from Phase 4, the quantified rankings produce a cardinal version of the Phase 3 ordinal risk matrix.

Table 10: NMD Example--Quantified Matrix

Effect \ Likelihood	[0, .05)	[.05, .1)	[.1, .2)	[.2, .7)	[.7, 1]
Catastrophic	S44 S59 S62	S2 S4			
Critical		S7 S56	S46		
Serious					S38
Moderate					S16
Marginal					

Low Risk	Moderate Risk	High Risk	Extremely High Risk

Phase 6: Risk Management: In this phase, the risk management options to deal with risk scenarios are identified and compared based on the cost, benefits, and risk reduction. From a DoD perspective, this is the phase to consider the traditional risk handling options of Control, Transfer, Avoidance, and Acceptance.

Phase 7: Safeguarding Against Missing Critical Items: In this phase it is important to take stock of the progress so far. It is possible that in reducing the initial risk scenarios to a smaller set scenarios may have filtered out that, while seeming minor at the time, may actually become important if the risk management options developed in Phase 6 are implemented. So Phase 7 is an opportunity to evaluate the performance of Phase 6 options against previously filtered scenarios. The guiding principle in this phase is the system's intra-dependencies and interdependencies that may have been overlooked.

Each of the remaining scenarios is examined to determine whether it is dependent upon any filtered scenario. If a filtered scenario is significantly impacted, then it must be returned to the table for consideration and risk management.

Phase 8: Operational Feedback: This final phase uses the experience and information gained during implementation of the chosen option(s) to refine the scenario filtering and decision processes of earlier phases. Of course, this phase is not possible on the first iteration, but can be invaluable for adjusting assumptions when reworking the scenarios.

2.5. Analyzing Variables (Decision Trees and Risk Profiles)

In addition to developing and filtering scenarios, there are several decision analysis techniques to aid in the final determination. One example of particular value to this research is a decision analysis approach employed to consider installing anti-missile systems on commercial aircraft (von Winterfeldt, 2006). The authors first established relevant variables that could impact a decision maker's choices (e.g., cost of the system, cost of the plane, value of life, etc.). They then used open source information to establish a reasonable minimum, maximum and base case value for each variable. Using this information they created a logical decision tree to explore the expected economic effects a terrorist strike w/MANPADS would have on the airline industry and U.S. economy.

Interestingly, the researchers discovered that many of the variables one might normally consider in a decision actually had no impact on the decision outcome when subjected to sensitivity analysis. For example, loss of life, even when valued at $10M per person on a 400 person passenger jet, was not a significant factor in deciding whether or not to install the anti-missile system. Instead, the riving force turned out to be the impact to the transportation industry and the entire U.S. economy.

This technique seems to have value for applying decision analysis to future scenarios as well. Even though no exact values of relevant variables are available, it is still possible to generate a range a values that most experts would agree upon. While the wide range may, in some cases, limit the usefulness of the analysis, it may also demonstrate that the values of some variables are irrelevant and do not merit research or discussion. This type of focusing tool could be extremely useful when deciding where to apply research and development resources.

In addition to demonstrating the powerful application of sensitivity analysis to an aerospace industry problem, the authors also showed that a risk profile could present a strong visual impression to a decision maker (Figure x, below). The visual representation of expected equivalent cost against the probability of incurring those costs can be quickly overlaid onto a decision maker's risk preferences. For example, investing in countermeasures (CM) will most likely incur costs in to the \$10B-\$19B range. But not installing the system exposes the DM to a 1 in 10 chance of incurring a \$100B+ consequence.

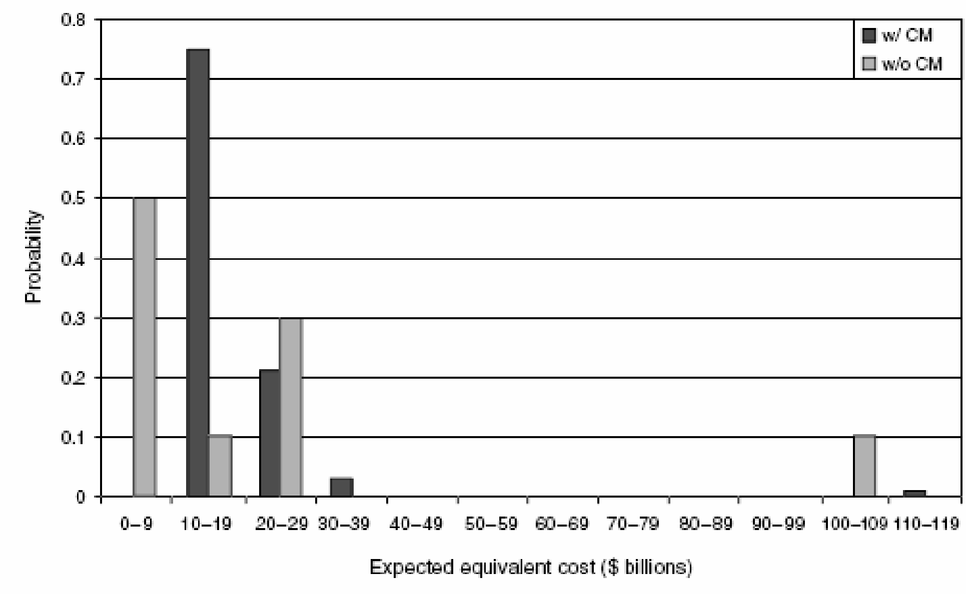

Figure 5: Expected Equivalent Costs vs. Probability

2.6. Summary

There are three primary areas that will form the foundation of this research. To create the scenario space and provide a context for threat technologies, this research examined several germane alternative futures posited by experts over the course of five comprehensive future world studies. To provide a framework for evaluating specific threat technologies, the Threat Warning System of the National Intelligence Council was established the foundation document, which will be supported by multiple secondary sources for scenario development. Finally the Risk Filtering Ranking and Management (RFRM) process was explored and validated as a possible technique to capture, evaluate and select relevant threat scenarios for consideration by design teams and decision makers working on the global strike vehicle concept for the US Air Force.

3. Identification of Risk Scenarios

There are three elements to the process that will ultimately support this research and aid the Air Force Research Lab (AFRL) design decision strategy. The first is the development of a Hierarchical Holographic Model (HHM) that will identify the elements of the air vehicle that are most vulnerable to technology inspired risk scenarios. The second element (and part of the HHM process) is the creation of a scoring mechanism to weigh the likelihoods of each scenario within the context of an alternative future. The final piece will be to evaluate candidate scenarios that would benefit the decision maker through further development and analysis.

3.1. HHM Assumptions (framing the analysis)

Like all modern weapon systems, any US Air Force global strike vehicle will likely be designed as an integrated element of a larger "system of systems" (Figure 6) This is relevant for two reasons. First, all of the major systems must work properly for the strike vehicle to operate. So, for the purpose of this research, if a system is substantially damaged, it will be considered inoperative in the scenarios developed. Second, even though a thorough systems approach would consider external elements beyond the strike vehicle system boundary, this research will focus solely on the area inside the strike vehicle system boundary and on direct threats to the strike vehicle. Consequently, Command and Control (e.g., external data links network), Logistics Support (e.g., aerial refueling), Navigation Signals (GPS Constellation), and communications (COMSAT), will not be considered as interdiction targets for the enemy—even though striking these nodes could derail the mission just as effectively as destroying the strike vehicle. Additionally, the offensive weapon systems of the strike vehicle will not be considered in the analysis. Even though the failure of the weapon to successfully engage its intended target may result in mission failure, such a failure is not relevant to the survival of the strike vehicle and developing defensive systems for that vehicle.

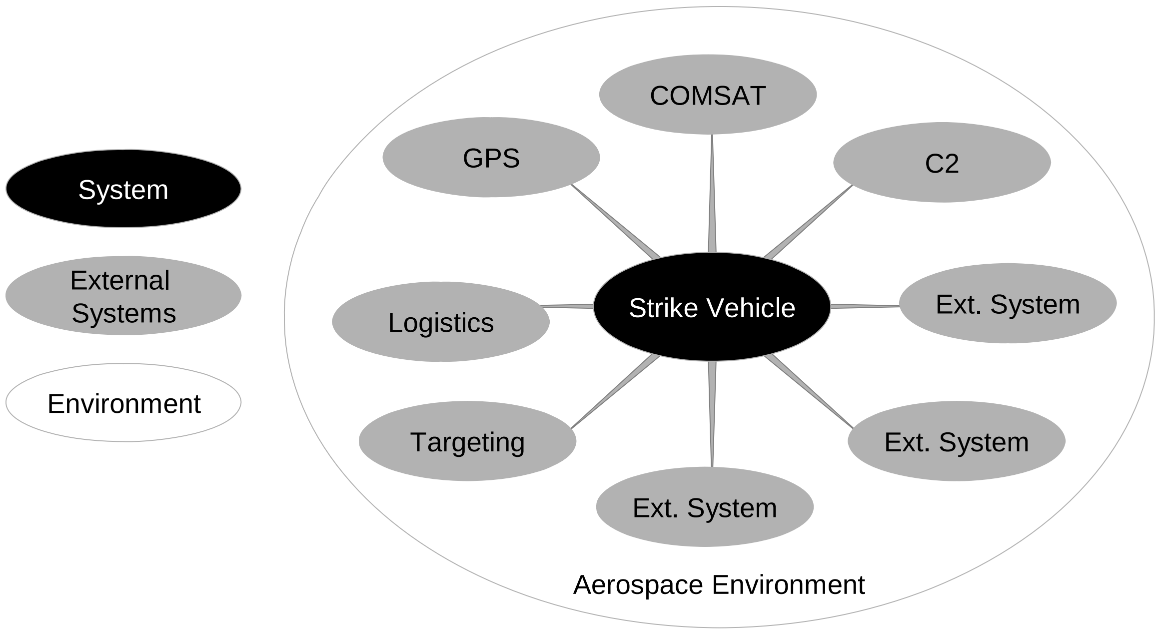

Figure 6: System Boundary Diagram

3.2. Building the HHM

A basic HHM for an aircraft system should contain at least the following areas of concern: Avionics, Propulsion, Structure, Payload, Landing Gear, Defensive Systems, Power and Software. Likewise, the head topics for the HHM (Figure 7) should mirror those same areas.

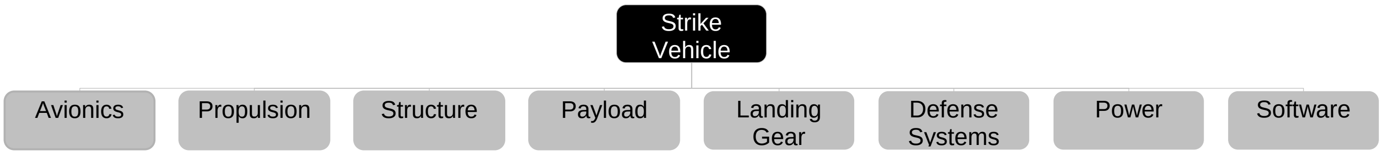

Figure 7: Strike Vehicle Top Level HHM

Once these head topics are established they can be broken down into sub-areas that have relevance to the problem under consideration (Figure 8). Ideally, each head topic should be decomposed to a low enough level to ensure there is little or no overlap between areas of interest and allow decision makers to filter out areas of little concern.

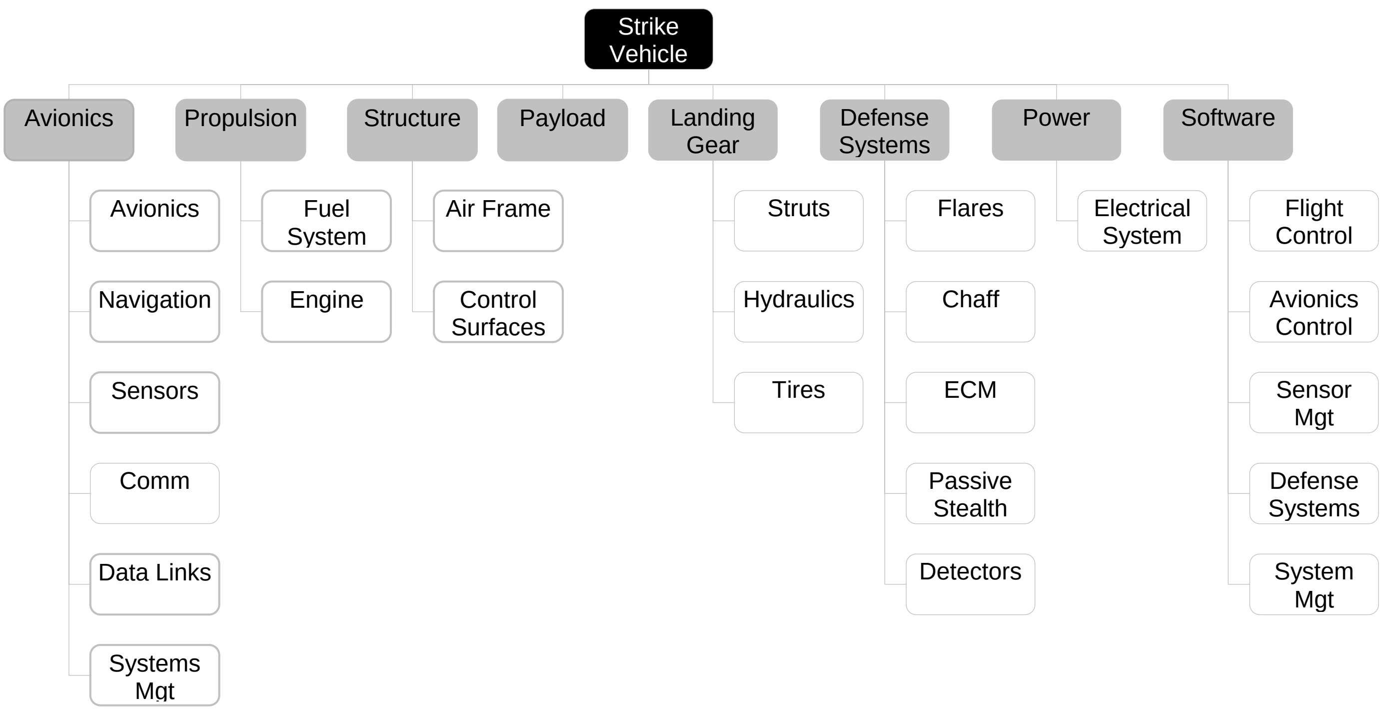

Figure 8: Strike Vehicle Expanded HHM

3.3. Initial Filtering Based on Decision Maker's Perspective

In the case of the global strike vehicle, the AFRL (for this project) is principally concerned with direct threats to strike vehicle survival in enemy air space. Consequently some of these topics can be immediately truncated from the perspective of the decision maker (Figure 9). Of particular note are the Payload system, the Landing Gear system and the Software system. The payload (i.e. weapon load), while certainly important for successfully completing the mission, is not a factor to consider in developing strike vehicle survival systems. Likewise, the landing gear—important for take off and landing—is not a significant factor in developing threat scenarios. Software, while obviously important for the design and operation of the system, is not directly targetable by projected enemy defensive systems. Though the systems controlled by the software are certainly targets of enemy air defenses, it is the physical failure of those systems that is of importance here, so there do not seem to be any significant ties that require the decision maker to keep the software tree on the HHM.

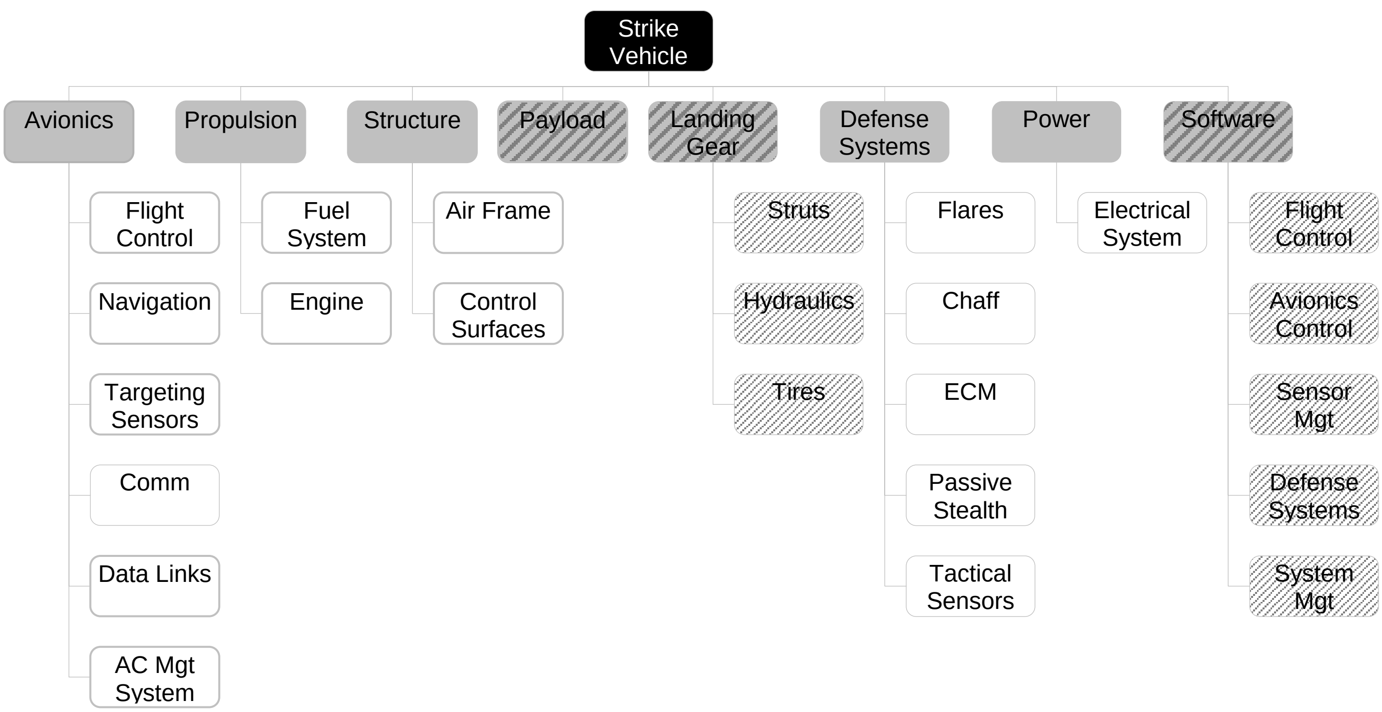

Figure 9: Strike Vehicle HHM with Initial Redactions

3.4. Scenario Generation from the HHM Decomposition

From this revised array of subtopics, one can develop several rudimentary scenarios based on the general categories of threats indicated in the research. For review, the major threat categories under consideration are Advanced Missile Systems, Directed Energy Systems, Electromagnetic Pulse Systems, and Advanced Detection Systems. The scenarios proposed are believed to capture the most significant impacts certain weapons effects could have on a typical military strike aircraft. However, it is certainly possible that flight vehicle experts may be aware of other significant areas of vulnerability (published or unpublished) that could be used to broaden the scope of plausible scenarios. Extremely improbable scenarios were left off the list (e.g., crew incapacitated but vehicle otherwise fully operational), as well as those that posited outcomes with negligible consequences (e.g., temporary disruption in voice comm. due to weak EMP interference).

3.4.1 Avionics

S1 - Flight Avionics (*EMP1*): An adversary employs MEMS to field very long range UAVs as a system of UAV-based EMP aerial mines as part of an IAD system. A non-nuclear, wide area Electro-Magnetic (EM) burst from a UAV aerial mine completely overloads and disables the strike vehicle sensors, but flight control is unaffected.

S1a - Flight Avionics (*EMP2*): An adversary employs MEMS to field very long range Surface to Air Missiles. A non-nuclear, wide area EM burst from an EMP missile completely overloads and temporarily disables the strike vehicle flight control systems.

S2 - Navigation (*EMP1*): An adversary employs MEMS to field very long range UAVs as a system of UAV-based EMP aerial mines as part of an IAD system. A non-nuclear, wide area Electro-Magnetic (EM) burst from a UAV aerial mine completely overloads and disables the strike vehicle navigation systems.

S2a - Navigation (*EMP2*): An adversary employs MEMS to field very long range Surface to Air Missiles. A non-nuclear, wide area EM burst from an EMP missile completely overloads and temporarily disables the strike vehicle navigation systems.

S3 - Navigation (*Conventional*): An adversary employs advanced algorithms and high speed processors in a multi-seeker missile system to increase ability to lock on to desired target—partially negates current physical and EW defense measures. A missile warhead with a conventional explosive detonates close enough to project shrapnel into the strike vehicle—damaging the strike vehicle navigation systems.

S4 - Sensors (*EMP1*): An adversary employs MEMS to field very long range UAVs as a system of UAV-based EMP aerial mines as part of an IAD system. A non-nuclear, wide area Electro-Magnetic (EM) burst from a UAV aerial mine completely overloads and disables the strike vehicle sensor systems.

S4a - Sensors (*EMP2*): An adversary employs MEMS to field very long range Surface to Air Missiles. A non-nuclear, wide area EM burst from an EMP missile completely overloads and temporarily disables the strike vehicle flight sensor systems.

S5 - Sensors (*Conventional*): An adversary employs MEMS to field very long range Surface to Air Missiles. A missile warhead with a conventional explosive is diverted from the strike vehicle by countermeasures, but still detonates close enough to the strike vehicle to disable multiple sensors (e.g., radar, IR, etc.)

S6 - Communications (*EMP1*): An adversary employs MEMS to field very long range UAVs as a system of UAV-based EMP aerial mines as part of an IAD system. A non-nuclear, wide area Electro-Magnetic (EM) burst from a UAV aerial mine completely overloads and disables the strike vehicle communications systems.

S6a - Communications (*EMP2*): An adversary employs MEMS to field very long range Surface to Air Missiles. A non-nuclear, wide area EM burst from an EMP missile completely overloads and temporarily disables the strike vehicle flight communications systems.

S7 - Communications (*Conventional*): An adversary employs MEMS to field very long range Surface to Air Missiles. A missile warhead with a conventional explosive is diverted from the strike vehicle by countermeasures, but still detonates close enough to the strike vehicle to disable the communications array.

S8 - Data Links (*EMP1*): An adversary employs MEMS to field very long range UAVs as a system of UAV-based EMP aerial mines as part of an IAD system. A non-nuclear, wide area Electro-Magnetic (EM) burst from a UAV aerial mine completely overloads and disables the strike vehicle flight data links.

S8a - Data Links (*EMP2*): An adversary employs MEMS to field very long range Surface to Air Missiles. A non-nuclear, wide area EM burst from an EMP missile completely overloads and temporarily disables the strike vehicle flight data links.

S9 - Data Links (*Conventional*): An adversary employs MEMS to field very long range Surface to Air Missiles. A missile warhead with a conventional explosive is diverted from the strike vehicle by countermeasures, but still detonates close enough to the strike vehicle to disable the data links.

S10 - Aircraft Management System (*EMP1*): An adversary employs MEMS to field very long range UAVs as a system of UAV-based EMP aerial mines as part of an IAD system. A non-nuclear, wide area Electro-Magnetic (EM) burst from a UAV aerial mine completely overloads and disables the strike vehicle aircraft management system.

S10a - Aircraft Management System (*EMP2*): An adversary employs MEMS to field very long range Surface to Air Missiles. A non-nuclear, wide area EM burst from an EMP missile completely overloads and temporarily disables the strike vehicle aircraft management system.

3.4.2 Propulsion

S11 - Fuel System (*Conventional*): An adversary employs advanced algorithms and high speed processors in a multi-seeker missile system to increase ability to lock on to desired target—partially negates current physical and EW defense measures. A missile warhead with a conventional explosive detonates close enough to project shrapnel into the strike vehicle—damaging the strike vehicle fuel system.

S12 - Fuel System (*DEW*): An adversary fields a long range, ground-based directed energy weapon (400+ miles)—effectively nullifying existing threat countermeasures designed for diverting missiles. A DEW burst (Laser) ignites the internal strike vehicle fuel bladders, causing spontaneous combustion of the vehicle.

S13 - Engine (*Conventional*): An adversary fields a highly sensitive, integrated IR detection system that can sense extremely low levels of IR radiation from strike vehicle heat sources—effectively degrading the IR stealth features of the strike vehicle. An IR missile with a conventional explosive locks on the strike vehicle's engine exhaust, penetrates through the weakened defensive systems and effectively destroys the strike vehicle engine.

3.4.3 Structure

S14 - Air Frame (*Conventional*): An adversary employs advanced algorithms and high speed processors in a multi-seeker missile system to increase ability to lock on to desired target—partially negates current physical and EW defense measures. A missile warhead with conventional explosives detonates close enough to project shrapnel into the strike vehicle—critically degrading multiple airframe components.

S15 - Control Surfaces (*Conventional*): An adversary employs advanced algorithms and high speed processors in a multi-seeker missile system to increase ability to lock on to desired target—partially negates current physical and EW defense measures. A missile warhead with conventional explosives detonates close enough to project shrapnel into the strike vehicle—damaging multiple flight control surfaces.

3.4.4 Defensive Systems

S16 - Flares/Chaff Damaged (*Conventional*): An adversary fields an integrated, multi-static radar detection system that can defeat current USAF passive RF stealth technology—effectively degrading the passive stealth system. The adversary launches a large salvo of SAMs in the vicinity of the strike vehicle, and at least one a missile warhead with a conventional explosive detonates close enough to project shrapnel into the strike vehicle—disabling the strike vehicle flare dispenser, chaff dispenser and/or EW transmission hardware

S17 - Flares/Chaff/ECM Degraded (*Multiseeker technology*): An adversary fields a long range multi-seeker missile system powered by small jet engines that are difficult to detect on the vehicles on-board RF/IR/Optical detection systems—effectively creating a smart, stealthy missile that will ignore chaff, flares and even some EW.

S18 - ESM/DAS degraded (*smart/stealthy missiles*): An adversary employs advanced algorithms and high speed processors in a multi-seeker missile system to increase ability to lock on to desired target—partially negates current physical and EW defense measures.

S19 - ESM/DAS destroyed (*EMP1*): An adversary fields a system of UAV-based EMP aerial mines as part of an IAD system. A non-nuclear, wide area Electro-Magnetic (EM) burst from a UAV aerial mine completely overloads and disables the strike vehicle electrical system.

S19a - ESM/DAS damaged (*EMP2*): An adversary employs MEMS to field very long range Surface to Air Missiles. A non-nuclear, wide area EM burst from an EMP missile completely overloads and temporarily disables the strike vehicle Defensive Aids System (DAS).

S20 - Passive Stealth degraded (*Conventional*): A missile warhead with a conventional explosive detonates close enough to project limited shrapnel into the strike vehicle—the aircraft is unaffected except that the stealth skin of the strike vehicle is impacted, significantly degrading its stealth properties and making it vulnerable to conventional on-board missile tracking systems.

S21 - Passive Stealth degraded (*Multi-static*): An adversary fields an integrated, multi-static radar detection system that can defeat current USAF passive RF stealth technology—effectively degrading the passive stealth system.

S21a - Passive Stealth degraded ("Multi-Static" *cellular networks*): An adversary utilizes ambient RF signals to create a virtual detection array capable of sensing vehicles employing passive stealth systems—effectively degrading the passive stealth system.

S22 - Passive Stealth degraded (*DEW*): An adversary fields an airborne, medium range directed energy weapon. The DEW (laser) manages to superheat and warp the passive stealth skin of the strike vehicle without detection—effectively nullifying the stealth properties and making the vehicle vulnerable to less capable IADs components.

3.4.5 Power

S23 - Electrical System (*EMP*): An adversary fields a system of UAV-based EMP aerial mines as part of an IAD system. A non-nuclear, wide area Electro-Magnetic (EM) burst from a UAV aerial mine completely overloads and disables the strike vehicle electrical system.

3.5. Bi-criteria Filtering

After establishing the pool of scenarios, the next step is to subject each scenario to the bi-criteria filtering process—essentially assigning a likelihood and consequence to each scenario to determine the potential impact each scenario outcome could have on the strike vehicle mission. While the process sounds rudimentary, it is perhaps the most important step for guiding the decision maker's strategy. Additionally, since all of the scenarios under review are projections of possible systems in the future, it is necessary to devise a credible means of assigning probabilities to each.

To determine the likelihood of a given scenario, this research first considers the technical requirements. In the National Intelligence Council's evaluation, each technology under consideration was determined to be of very low threat or scored progressively as Watch, Warning or Alert—which equates nicely to an very high, high, moderate or low requirement for technical advancement. For example, the "alert" technologies are practically in the field now, so an advanced technology future is not necessarily required to bring them to fruition (though a robust economy may be necessary). Similarly, each of the candidate technologies is scored as a level 1, 2 or 3 for financial and resource accessibility. According to the technology estimate, level 3 technologies would likely require the resources of a significant state actor (or extremely powerful non-state actor), while level 2 technologies would likely be attainable within the means of well supplied non-state actors. This being the case, there is still the requirement to control large areas of territory for effective employment of detection systems and there is still the overriding consideration of the technological and economic environment of the future under consideration.

3.6. Predicting the Future

In all five alternative futures studies examined for this research, the assumption is made that the developed scenarios cover all possible futures--at least to the extent that the full range of futures is revealed given a set of controlling variables. Therefore, when assigning weights and considering alternatives, this research considers the data set at hand to be sufficiently complete and exhaustive.

In the NASA Study the National Academy of Sciences team did not associate a specific likelihood with each of the projected alternative futures so one might attach a default 1/16 chance of occurrence to each of the possible 16 scenarios. However, since the team's experts chose only 5 alternative futures as likely and useful for further study, and since the entire range of futures comes from the same matrix family, it could be argued that the remaining 11 are simply variations of the chosen 5. Therefore, for this exercise, each of the 5 scenarios will be given a 1/5 chance of developing. Using a similar rationale for the *SPACECAST 2020*, *AF 2025*, *NIC 2020* and *Army 2025* studies gives respective probabilities of 1/4, 1/4, 1/4 and 1/6 for each of their alternative futures.

It should be noted that each of the studies relies on several drivers to determine the alternative futures. Presumably a more detailed probability analysis could be constructed to address the probabilities of each individual driver. However, since those drivers and their values are, by default, given equal weight by the study teams, a more in-depth analysis would not produce more useful information—unless the goal was to adjust those weights. As a result, this research will consider the alternative futures themselves as a sufficient level at which to assign probabilities.

3.7. Probability of Fertile Environments for Advanced System Fielding

Based on the assumptions made by all the alternative futures studies reviewed for this research, and the practical considerations adopted by the Technology Warning Assessment methodology, there are two key factors that play into the fielding of advanced weapons systems that could conceivably compromise the US Air Force strengths of speed, altitude and stealth: Technological capability and Economic capability. The advanced capabilities and high-speed/high-altitude operating environment of a global strike vehicle are not likely to be impinged by scattered Man-Portable Air Defense Systems (MANPADs) or indeed, any piecemeal IADs. Instead, there must be a significant development effort to field advanced detection and defense systems. Additionally, there must be the vast economic resources available to fund the development, fielding and operation of the systems.

Each of the futures studies under review does provide insight into the likelihood of the proper conditions evolving to manifest credible threat systems. To begin, the types of futures naturally aggregate into two general categories: State Actor dominated futures, and Non-State Actor dominated futures. Neither category precludes the other, but instead indicates that a majority of the power falls into a certain category. For example, the *Mad Max Inc.* alternative future of SPACECAST 2020 posits a significant decline in the power of the nation state as global mega-corporations evolve into powerful economic and political leaders in the world. There will still be state actors, but the most significant power players will be the corporations that hold the capital and technical expertise. These actors will either replace or overwhelmingly influence existing political authorities.

Table 11: Break Out of State Actor/Non-State Actor Futures

	SPACECAST 2020	AIR FORCE 2025	NASA	NIC 2020	ARMY 2025
Primarily posits a few powerful State Actors	Space Faring Space Cast	King Kahn	Pushing the Envelope Trading Places Regional Tensions	DAVOS World Pax Americana	U.S. Unipolarity Democratic Peace Major Competitor Rising Competitive Multipolarity
Primarily posits powerful Non-State Actors	Rogues Mad Max Inc.	Zaibatsu Digital Cacophony Gulliver's Travails	Grounded Environmentally Challenged	A New Caliphate Cycle of Fear	Transnational Web Chaos/Anarchy

Table 11 shows the State Actor/Non-State Actor break out of the alternative futures in each of the studies under review. As long as several significant factors are taken into consideration, it may be reasonable to assume that each alternative future study is equally significant and that each scenario within a given study is equally weighted among its peers—thus allowing one to calculate the relative likelihood's of a particular future's occurrence. To support that assumption the following should be considered. In each of the studies, the authors made no overt effort to quantify the relative likelihoods of included scenarios. However they did make a qualitative cut and chose to put forward only a subset of their total possible futures for analysis. Since there did not appear to be any real constraint on the number of alternative futures each study could develop, this research considers the alternative futures chosen by each study to represent to total set of likely futures for that study. Additionally, while at least one study (SPACECAST 2020) suggested a particular alternative future as the "most likely", it did not indicate a relative degree of likelihood in any quantifiable way.

Another issue that should be addressed is that at least two of the studies (*SPACECAST* and *AF 2025*) were directly influenced by the same researcher (Parnell). This fact would naturally detract from any calculations assuming mutual exclusivity of the studies (as is assumed done in this research), but there are several mitigating factors that make the assumption reasonable. First, the studies were accomplished five years apart from each other with different goals in mind. Second, while the same principle researcher (Parnell) was involved in both studies the composition of the expert panels, and analysis teams were certainly a different mix of people between the two studies. Additionally, the methodology was such that one researcher would not be able to unduly skew the outcome. Therefore the results can be considered effectively independent for the sake of this research.

Table 12 shows the calculation of the State Actor versus Non-State Actor likelihoods. The result appears to show only a slight edge to the strong state dominated futures. But there is more that can be gleaned from the data.

Table 12: Likelihood of Each Alternative Future Type

	SPACECAST 2020	AIR FORCE 2025	NASA	NIC 2020	ARMY 2025	Result
State	0.5	0.25	0.6	0.5	0.67	
(x 1/5)	0.1	0.05	0.12	0.1	0.134	**0.504**
Non-State	0.5	0.75	0.4	0.5	0.33	
(x 1/5)	0.1	0.15	0.08	0.1	0.066	**0.496**

Since there is another essential element to the threat equation (i.e., technology), it is necessary to advance this method of inquiry further to uncover the probable scenarios that would produce the requisite technology environment. In fact, since most of the advanced technologies under consideration require significant scientific development and economic resources this research will be concerned only with those scenarios that are likely to produce a fertile development environment. Table 13 indicates the alternative futures that are indicative of high levels of technological development (H) and those that are projected to have a more stunted development curve (L).

Table 13: Break Out of State Actor/Non-State Actor Futures with Tech Indicator

	SPACECAST 2020	AIR FORCE 2025	NASA	ARMY 2025
Primarily posits a few powerful State Actors	Space Faring (H) Space Cast (H)	King Kahn (L)	Pushing the Envelope (H) Trading Places (H) Regional Tensions (H)	U.S. Unipolarity (H) Democratic Peace (H) Major Competitor Rising (H) Competitive Multipolarity (H)
Primarily posits powerful Non-State Actors	Rogues (L) Mad Max Inc. (L)	Zaibatsu (H) Digital Cacophony (H) Gulliver's Travails (L)	Grounded (L) Environmentally Challenged (L)	Transnational Web (H) Chaos/Anarchy (L)

From this data, one can again perform a likelihood analysis for the necessary economic and technology conditions. Table 14 shows the calculation of the High Tech versus Low Tech likelihoods. Because the methodology for the NIC 2020 study does not clearly indicate a consistent measure for technology or economy in its scenarios, it cannot be included in the mix for determining technology development. The result appears to show a significant propensity for the various alternative futures to support robust technological development.

Table 14: Likelihood of Each Alternative Future w/Tech Indicator

	SPACECAST 2020	Air Force 2025	NASA	Army 2025	Result
High Tech	0.5	0.5	0.6	0.833	
(x 1/4)	0.125	0.125	0.15	0.208	**0.608**
Low Tech	0.5	0.5	0.4	0.167	
(x 1/4)	0.125	0.125	0.1	0.042	**0.392**

The relevant question then migrates to conditional likelihoods. Given the prerequisite of a high-technology environment to generate *and field* advanced weapon systems, what is the likelihood of the design/fielding agent being a state actor and what is the likelihood of the design/fielding agent being a non state actor? As the calculations below indicate, a high technology world of the future is much more likely to be a state actor dominated world than a non-state actor dominated world.

$$\textbf{P (State | High Tech)} = \frac{\text{P (High Tech | State) * P (State)}}{\text{P (High Tech)}} = \frac{0.917 * 0.504}{0.597} = \mathbf{0.774}$$

P (State) = 0.504

P (High Tech) = 0.504 (11/12) + .496 (3/11) = 0.597

P (High Tech | State) = 11/12 = 0.917

$$\textbf{P (Non State | High Tech)} = \frac{\text{P (High Tech | Non State) * P (Non State)}}{\text{P (High Tech)}} = \frac{0.273 * 0.496}{0.597} = \mathbf{0.227}$$

P (Non State) =0.496

P (High Tech) = 0.504 (11/12) + .496 (3/11) = 0.597

P (High Tech | Non State) = 3/11 = 0.273

Given a high likelihood of a high technology and robust economy future ("Technomic" in the language of AF 2025) one can then evaluate the threat scenarios in the context of the National Research Council's (NRC) technology evaluations. Since the NRC's assessment study was targeted at the 2015 it is necessary to consider some adjustments based on the type of future being considered. For example, in the world of 2025-2035 there will have been an additional 10-20 years for development projects to progress, so it is reasonable to adjust the evaluations upward for a high "Technomic" future. In the same way, a stunted future may indicate that the projections for 2015 would be shifted into a slower development pattern—reducing the expected maturity of reviewed technologies. Since this research is primarily concerned with a high "Technomic" future, it will graduate the existing technology maturity evaluations to the next highest level. For example, if a particular technology was evaluated as "Alert" in the NRC study it would normally be given a "High" likelihood rating. Instead, it will be given a "Very High" rating. Similarly, technologies that that were considered but not originally rated at the lowest level (watch) and would have been given a "low" likelihood will now be considered to have a "moderate" rating.

Given that that the high tech future is expected to manifest with a 60% probability and a low tech future at 40% probability, it is clear (assuming the validity of the calculations) that there is a fairly decent likelihood that the future will not produce the environment required for the development of advanced threat systems. Taking the approach of only planning for the high tech future indicates a certain amount of risk-averse thinking. However, there are several factors that make this approach the most logical to take:

1) The data (as presented and understood) projects a significantly higher likelihood of a high tech future.

2) Two of the studies used for the calculations took place before 9-11, before the current Iraq war, and before the resurgence of the global economy following the "dot com" collapse of the 1990's. Therefore they may not have fully appreciated the power of today's state actors and the global economy.

2) Military decision makers are not prone to take unnecessary risks with national security issues and matters of global power projection. So they would likely take the course of covering as many bases as possible (within budget constraints).

3) Taking a risk seeking approach in this instance would require the decision maker to take no action (or limited action) to mitigate projected threats—hardly a prudent course for the United States in today's political environment.

Through a similar line of thinking, there does not appear to be much utility in pursuing calculations for other conditional probabilities (e.g., Probability of Non-State Actors given a Low Tech future). A solid majority (60%) of the available probability rests with the State Actor/High Tech futures, and the other risk-averse rationale apply as well.

3.8. Evaluation of Consequences

To evaluate consequences, the following criteria will be used. An outcome that would result in the imminent destruction of the strike vehicle will be considered catastrophic. An outcome that would severely impair vehicle operation but allow for additional operation time before destruction will be considered critical. An outcome that would significantly degrade or disables multiple flight systems or defensive systems—but allows continued operation will be considered serious. An outcome that would significantly degrade multiple vehicle systems or disables a non-flying system, but still allow the vehicle to complete the mission at increased risk or abort the mission and return will be considered moderate. An outcome that impacts vehicle systems (temporarily or permanently) but still allows mission completion with near full capability will be considered marginal.

For the bi-criteria filtering phase of the Risk Filtering Ranking and Management (RFRM) process, this research will use the technology maturity level of the enabling technologies to determine the likelihood of a fielded system possessing the required capabilities to bring about the effect of the scenario (see Table 15).

Table 15: Evaluated Scenarios

Scenario	Likelihood	Consequence
Avionics		
S1 - Flight Avionics (*EMP1*)	High	Catastrophic
S1a - Flight Avionics (*EMP2*)	High	Critical
S2 - Navigation (*EMP1*)	High	Moderate
S2a - Navigation (*EMP2*)	High	Moderate
S3 - Navigation (*Conventional*)	Low	Moderate
S4 - Sensors (*EMP1*)	High	Serious
S4a - Sensors (*EMP2*)	High	Serious
S5 - Sensors (*Conventional*)	Moderate	Serious
S6 - Communications (*EMP1*)	High	Moderate
S6a - Communications (*EMP2*)	Very High	Moderate
S7 - Communications (*Conventional*)	Moderate	Moderate
S8 - Data Links (*EMP1*)	High	Moderate
S8a - Data Links (*EMP2*)	Very High	Moderate
S9 - Data Links (*Conventional*)	Low	Moderate
S10 - Aircraft Management System (*EMP1*)	High	Critical
S10a - Aircraft Management System (*EMP2*)	Very High	Critical
Propulsion		
S11 - Fuel System (*Conventional*)	Low	Critical
S12 - Fuel System (*DEW*)	Low	Catastrophic
S13 - Engine (*Conventional*)	High	Catastrophic
Structure		
S14 - Air Frame (*Conventional*)	High	Critical
S15 - Control Surfaces (*Conventional*)	High	Serious

Scenario	Likelihood	Consequence
Defensive Systems		
S16 - Flares/Chaff Damaged (*Conventional*)	Moderate	Serious
S17 - Flares/Chaff/ECM Degraded (*Multiseeker technology*)	High	Serious
S18 - ESM/DAS degraded (*smart/stealthy missiles*)	High	Serious
S19 - ESM/DAS destroyed (*EMP1*)	High	Serious
S19a - ESM/DAS damaged (*EMP2*)	High	Critical
S20 - Passive Stealth degraded (*Conventional*)	Moderate	Serious
S21 - Passive Stealth degraded (*Multi-static*)	High	Serious
S21a - Passive Stealth degraded (*cellular networks*)	High	Moderate
S22 - Passive Stealth degraded (*DEW*)	Low	Serious
Power		
S23 - Electrical System (*EMP*)	High	Catastrophic

Once all the scenarios have been identified and rated on the likelihood / consequences scale, they can be transcribed on to the risk matrix to evaluate their severity. As shown in Table 15, the different scenarios cover the spectrum of severity ratings—bringing into play to next filtering step of the RFRM process. Obviously the cut could be made at any point by the decision maker; who must consider the resources available to address each risk scenario. However, common business practice seems to indicate that it is reasonable to focus the risk mitigation effort and guard against over commitment of limited resources. To that end, this research will focus the remaining analysis on those scenarios that present either a High Risk or an Extremely High Risk as indicated on the severity matrix.

Table 16: Severity Matrix

	Very Low	Low	Moderate	High	Very High
Catastrophic		S12		S1 S13 S23	
Critical		S11		S1a S10 S14 S19a	S10a
Serious		S22	S5 S16 S20	S4 S4a S15 S17 S18 S19 S21	
Moderate		S3 S9	S7	S2 S2a S6 S8 S21a	S6a S8a
Marginal					

Low Risk	Moderate Risk	High Risk	Extremely High Risk

Making the cut at the High Risk level reduces the original 31 scenarios to a more manageable (and urgent) list of 19 scenarios (Table 16). It is still important to maintain the original scenarios. This practice allows for revisiting scenarios later in the process to ensure modeling decisions have not created new vulnerabilities or increased the severity of those scenarios previously filtered.

Table 17: Scenarios Bi-Criteria Cut Matrix

Scenario	Likelihood	Consequence
Avionics		
S1 - Flight Avionics (*EMP1*)	High	Catastrophic
S1a - Flight Avionics (*EMP2*)	High	Critical
S2 - Navigation (*EMP1*)	High	Moderate
S2a - Navigation (*EMP2*)	High	Moderate
S3 - Navigation (*Conventional*)	Low	Moderate
S4 - Sensors (*EMP1*)	High	Serious
S4a - Sensors (*EMP2*)	High	Serious
S5 - Sensors (*Conventional*)	Moderate	Serious
S6 - Communications (*EMP1*)	High	Moderate
S6a - Communications (*EMP2*)	Very High	Moderate
S7 - Communications (*Conventional*)	Moderate	Moderate
S8 - Data Links (*EMP1*)	High	Moderate
S8a - Data Links (*EMP2*)	Very High	Moderate
S9 - Data Links (*Conventional*)	Low	Moderate
S10 - Aircraft Management System (*EMP1*)	High	Critical
S10a - Aircraft Management System (*EMP2*)	Very High	Critical
Propulsion		
S11 - Fuel System (*Conventional*)	Low	Critical
S12 - Fuel System (*DEW*)	Low	Catastrophic
S13 - Engine (*Conventional*)	High	Catastrophic
Structure		
S14 - Air Frame (*Conventional*)	High	Critical
S15 - Control Surfaces (*Conventional*)	High	Serious

Scenario	Likelihood	Consequence
Defensive Systems		
S16 - Flares/Chaff Damaged (*Conventional*)	Moderate	Serious
S17 - Flares/Chaff/ECM Degraded (*Multiseeker technology*)	High	Serious
S18 - ESM/DAS degraded (*smart/stealthy missiles*)	High	Serious
S19 - ESM/DAS destroyed (*EMP1*)	High	Serious
S19a - ESM/DAS damaged (*EMP2*)	High	Critical
S20 - Passive Stealth degraded (*Conventional*)	Moderate	Serious
S21 - Passive Stealth degraded (*Multi-static*)	High	Serious
S21a - Passive Stealth degraded (*cellular networks*)	High	Moderate
S22 - Passive Stealth degraded (*DEW*)	Low	Serious
Power		
S23 - Electrical System (*EMP*)	High	Catastrophic

As stated, the process thus far has produced 19 scenarios; however, further filtering is necessary to focus limited resources on the problematic scenarios for mitigation planning and action. Using Haimes' 11 criteria each of the remaining scenarios is rated as High, Medium or Low (or Non Applicable) in each area (Table 18).

Table 18: 11 Criteria Evaluation

Criteria	S1	S1a	S2	S2a	S4	S4a	S6	S6a	S8	S8a	S10	S10a	S11	S12	S13	S14	S15	S17	S18	S19	S19a	S21	S21a	S23
Undetectability	M	L	M	L	M	L	M	L	M	L	M	L	M	H	L	L	L	M	H	M	L	H	H	M
Uncontrollability	H	H	M	M	M	M	H	M	M	L	M	L	H	H	H	H	M	H	H	M	M	M	M	H
Multiple Failure Paths	H	H	L	L	M	M	L	L	L	L	M	M	H	H	H	H	H	M	M	H	H	M	M	H
Irreversibility	H	M	H	L	H	M	H	L	H	L	H	M	H	H	H	H	H	M	M	H	M	M	M	H
Duration of Effects	H	M	H	L	H	M	H	L	H	L	H	M	H	H	H	H	H	H	H	H	M	H	H	H
Cascading Effects	H	M	L	L	M	M	L	L	L	L	M	M	H	H	H	H	H	M	M	M	M	M	M	H
OpsEnvironment	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
Wear and Tear	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
HW/SWHU/OR	H	H	M	M	M	M	L	L	L	L	H	H	L	L	L	L	M	M	M	M	M	L	L	H
Complexity	H	H	H	H	H	H	M	M	M	M	H	H	H	H	H	H	H	M	M	M	M	M	M	H
Design Immaturity	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Total L	0	1	2	5	0	1	3	6	3	7	0	2	1	1	2	2	1	0	0	0	1	1	1	0
Total M	3	5	5	4	7	8	4	4	5	3	6	6	3	2	2	2	4	8	7	7	8	7	7	3
Total H	7	4	3	1	3	1	3	0	2	0	4	2	6	7	6	6	5	2	3	3	1	2	2	7
Total of L=1, M=2, H=3	27	23	21	16	23	20	20	14	19	13	24	20	25	26	24	24	24	22	23	23	20	21	21	27

Ideally, this process leaves the most severely mission-impacting scenarios to analyze and address for mitigation efforts. However, since the RFRM process literature does not provide a method for culling scenarios based on the 11 criteria, it falls to the researcher to devise a logical selection scheme.

One approach would be to select those scenarios with the highest occurrences of High impacts. Using 6 as the threshold would produce a list of six scenarios that have the potential for the most extreme impact on the strike vehicle. Another technique would be to assign a point value to each rating level (L=1, M=2, H=3) resulting in a maximum score of 30 and a minimum score of 10 (since Design Immaturity is N/A for all scenarios). This technique still puts more weight on the High impact items, but also allows Moderate and Low risk items to be considered in the evaluation (though still in a qualitative way). The number of scenarios to be retained is simply based on where the cut line is drawn. At a score of 24 there are 8 scenarios, while dropping the bar to 23 raises the total 13. It should be noted that each technique may exclude scenarios included by the other approach, so it is important to look at the complete picture—not just focus on the calculated numbers. For this study, however, assigning points to each evaluation level ends up including all of the scenarios that would have been included in the extreme event approach, so this research will use the point system and draw the line at 24. Table 19 shows the final scenarios to be analyzed for the threat mitigation plan of the decision maker.

Table 19: Scenarios Multi-Criteria Cut Matrix

Scenario	Likelihood	Consequence
S1 - Flight Avionics (*EMP1*)	High	Catastrophic
S10 - Aircraft Management System (*EMP1*)	High	Critical
S11 - Fuel System (*Conventional*)	Low	Critical
S12 - Fuel System (*DEW*)	Low	Catastrophic
S13 - Engine (*Conventional*)	High	Catastrophic
S14 - Air Frame (*Conventional*)	High	Critical
S15 - Control Surfaces (*Conventional*)	High	Serious
S23 - Electrical System (*EMP*)	High	Catastrophic

3.9. Summary

The RFRM methodology, when combined with the alternative futures review and technical assessments has allowed for the generation and qualitative down selection of several threat scenarios. These scenarios, while useful in their current state, now require further analysis and understanding to effectively assist the decision maker in making development investments to counter likely threat technologies.

4. Scenario Analysis

Once the number of scenarios has been filtered down to a workable group of threats, they must be analyzed and transformed into actionable vectors to mitigate those threats. In the Risk Filtering Ranking and Management (RFRM) process, this is represented as a shift in the analysis from the qualitative to the quantitative—followed by the development of management strategies. However, since the problem under review concerns imprecise predictions about the future state of the world, an attempt to rigidly quantify the results would be highly speculative. Nonetheless, a qualitative analysis can still be performed and a management strategy is still possible to guide the design effort. The remainder of this chapter will be devoted to examining the selected scenarios and discussing mitigation options. It should be noted that though the mitigation discussions are based on the literature in Chapter 2 (as well as additional, non-scholarly sources like Global Security.org and the Federation of American Scientists) they are not meant to be considered definitive, completely exhaustive or even an expert opinion. Instead, they are meant to present a reasonable starting point and demonstrate the technique and process that could be used to further support and develop the Air Force Research Lab (AFRL) design effort.

In general, threat mitigation strategies should center on decreasing either the likelihood or the consequence (or both) of a particular scenario outcome. In each scenario (or group of scenarios) below, the analysis will consider several, logical, open-source options to reduce the scenario severity.

4.1. Electromagnetic Pulse (EMP) Threats

Scenario	Likelihood	Consequence
S1 - Flight Avionics (*EMP1*)	High	Catastrophic
S10 - Aircraft Management System (*EMP1*)	High	Critical
S23 - Electrical System (EMP)	High	Catastrophic

In addition to the technical assessments predicting the viability of Electromagnetic Pulse (EMP) weapons, it is also useful to employ visualization by aerospace technology pundits to help shape the concept space. Accordingly, and EMP style warhead could be employed with Air-to-Air Missiles and Surface-to-Air Missiles with varying platforms—possibly as envisioned below in the concepts portrayed by Global Security and AF 2025:

> *"Providing that compact electromagnetic warheads can be built…a number of other potential applications become viable. One is to equip an Air-Air Missile (AAM) with such a warhead…Loss of…EW equipment, mission computers, digital engine controls, communications and electronic flight controls…could render the victim aircraft defenseless against attack with conventional missiles…Area defense SAMs…could accommodate an electromagnetic warhead comparable in size to a bomb warhead…This has obvious implications for the electromagnetic hardness of combat aircraft systems."* (Global Security.Org)

> *"[An] airship whose purpose is to serve as a platform for an aerial mine system...[will]obtain operating ceilings of over 100,000 ft. and can remain airborne for periods exceeding one year…The airships would be autonomously operated via sensors and computers. It would use radar, infrared, or other devices to detect enemy air activity; upon which air to air missiles would automatically engage the enemy. A fleet of such craft could be used as aerial mines to make enemy airspace unusable…*"(Air Force 2025)

<u>Likelihood Mitigation:</u> The likelihood of experiencing a negative outcome can logically be reduced in several ways—each promising improvement, but at a cost.

1) Harden critical vehicle systems against the EMP threat. The required degree of hardening (i.e., EMP shielding) would depend on the anticipated intensity of the EMP, which is a factor of the pulse strength and the distance to the source. In general, the greater the shielding capacity, the greater will be the addition to vehicle weight. Increased vehicle weight will detract from vehicle performance (to varying degrees depending on design decisions) by reducing the maximum payload, reducing maximum range or degrading other flight characteristics (e.g., Radio Frequency (RF) stealth cross section).
2) Add enhanced sensors to the strike vehicle to improve chances of detecting small, stealthy aerial mines and either avoiding their area of effect or destroying their operating platform. Additional/more capable sensors will likely add to vehicle weight and modify the vehicle shape which presents the same concerns as above. If the "avoidance" tactic is chosen the vehicle will require additional range capability to ensure reaching the target after evasive maneuvers. If the "destroy the threat" tactic is employed the addition of an air-to-air strike capability would have to be added to the vehicle (kinetic or directed energy) which adds to vehicle weight and complexity and reduces the vehicle's strategic strike capacity.
3) Render the enemy defensive net ineffective by avoiding detection through enhancement of the stealth features of the US Air Force strike vehicle. This is a highly classified area of inquiry, but some general principles can be applied for discussion in this non-classified thesis. First, all things being equal (geometry, composition, etc.) a smaller vehicle will present a smaller radar cross section (in all wavelengths). Second, research could focus on increasing the effectiveness of

current radar absorbing material. Finally, recent research on active stealth technology (microwave frequency) may indicate a fruitful area of investment for multi-spectral active stealth technology.

Consequence Mitigation: The consequences of temporarily losing flight control are difficult to mitigate, as they would typically lead to the imminent demise of the air vehicle. However, there may be some design features that would allow the air vehicle to default into a stable flight configuration in the event of the loss of coherent control signals. While the lack of maneuverability may increase the risk of successful assault by other enemy weapons, it would also allow for the possibility of recovering vehicle control and either continuing the mission or retrieving the vehicle intact.

4.2. Directed Energy Weapon (DEW) Threats

Scenario	Likelihood	Consequence
S12 - Fuel System (*DEW*)	Low	Catastrophic

While only one of the directed energy weapon scenarios made it into the final list for evaluation, the potentially catastrophic effects make this a likely future weapon to be concerned with—especially since there is no defense against the threat today. The most visible scenario mirrors US Air Force efforts with the Airborne Laser (ABL) project, though ground-based Integrated Air Defense systems (IADs) projects are certainly feasible considering the greater energy reserves available for a ground based system. The ABL is designed to destroy enemy missiles in the boost phase but is equally viable as an anti-aircraft weapon.

> *"The ABL is designed to detect and destroy theatre ballistic missiles in the powered boost phase of flight immediately after missile launch. The aircraft loiters at an altitude of 40,000 feet. Missile launch is detected by a reconnaissance system such as satellite or Airborne Warning and Control System (AWACS) aircraft and threat data is transmitted to the ABL aircraft by Link 16 communications. A suite of infrared, wide-field telescopes installed along the length of the aircraft's fuselage detects the missile plume at ranges up to several hundred km...Where the missile carries liquid fuel, the laser can heat a spot on the missile's fuel tank, causing an increase in internal pressure resulting in catastrophic failure…"* (Air Force Technology.com)

Likelihood Mitigation

1) Shield the surface of the vulnerable area with a highly reflective coating. Unfortunately, that would also likely increase the radar cross section of the vehicle unless material was developed to be transparent to RF but opaque to visible light.
2) Construct the fuel storage tanks to withstand very high external temperatures and to radiate the energy back to the environment (may increase the IR signature).
3) Add sensors to the vehicle to detect thermal spikes and develop in-flight maneuvers to reduce the laser dwell time over any specific point on the vehicle.

Consequence Mitigation

1) Design fuel bladders to be able to release pressure without exploding (would still result in loss of fuel and reduced mission range)
2) Design the strike vehicle with a favorable glide ratio (and emergency weight management system to drop unneeded gear) so that a high altitude mission that lost its fuel source could still return to neutral territory.

4.3. Conventional Threats

The "conventional" threat scenarios are labeled as such because the agent of destruction is a simple, kinetic warhead on a standard missile (albeit with advanced materials, propulsion and electronics on board). Since that is the assumed case, the reduction in likelihood will be similar in many respects—illuminated by the following visual description.

> *"A broad-band multimode seeker system for a missile includes a wide band phased array transmitter/receiver unit incorporating a wafer scale phased array device with a bandwidth of about 2 GHz to 35 GHz. A multimode intermediate frequency unit selectively generates radar and jamming waveforms and measures parameters of reflected radar and external emissions of RF energy. A guidance processor manages the front end assets for selective active or semi active radar searching and tracking, and simultaneous searching for, tracking of, homing on, and applying a selection of electronic countermeasures to, multiple defensive radars. Confirmation of an assigned target is made through correlation of received RF signals with libraries of expected defensive system parameters and high resolution target profiles and preloaded target geographical coordinates."* (Freepatentsonline.com)

Scenario	Likelihood	Consequence
S11 - Fuel System (*Conventional*)	Low	Critical

<u>Likelihood Mitigation</u>

1) Install on-board, active, anti-missile system (e.g., small laser to blind missile seeker hardware). This option will add extra weight (for the sensor hardware and the weapon itself), increase the overall system complexity and would require additional design to incorporate into the stealth exterior.

2) Invest design dollars to reduce RF and IR signatures to minimize chance of detection and weapons lock.
3) Continue development on multi-spectrum jammers to divert the incoming missiles.
4) Increase the strike vehicle operational ceiling to allow more time for hostile missile detection and require more energy expenditure from the threat systems.

Consequence Mitigation

1) Design fuel bladders to be able to release pressure without exploding. This option would still result in loss of fuel which would reduce mission range, but could allow for strikes on secondary targets and for the recovery of the vehicle.
2) Design the fuel system with independently controllable, redundant fuel flow systems. While this option obviously adds to vehicle weight and complexity, it would also increase the vehicle survivability in the case of minimal vehicle damage.
3) Design the strike vehicle with a favorable glide ratio (and an emergency weight management system to drop unneeded gear) so that a high altitude mission that lost its fuel source could still return to neutral territory.

Scenario	Likelihood	Consequence
S13 - Engine (*Conventional*)	High	Catastrophic

Likelihood Mitigation

1) Install on-board, active, anti-missile system (e.g., small laser to blind missile seeker hardware). This option will add extra weight (for the sensor hardware and the weapon itself), increase the overall system complexity and would require additional design to incorporate into the stealth exterior.
2) Employ design concepts to further reduce the IR signature of the vehicle engine exhaust to decrease chances of a fatal engine impact (increased vehicle complexity).
3) Invest design dollars to reduce RF and IR signatures to minimize chance of detection and weapons lock.
4) Continue development on multi-spectrum jammers to divert the incoming missiles.
5) Increase the strike vehicle operational ceiling to allow more time for hostile missile detection and require more energy expenditure from the threat systems.

Consequence Mitigation

1) Design the strike vehicle with multiple engines sufficiently separated on the airframe to allow continued flight operations without one engine and with some structural damage (e.g., A-10 robust design). This would certainly add to the vehicle complexity, size and weight—which equate to performance tradeoffs.

Scenario	Likelihood	Consequence
S14 - Air Frame (*Conventional*)	High	Critical

Likelihood Mitigation

1) Install on-board, active, anti-missile system (e.g., small laser to blind missile seeker hardware). This option will add extra weight (for the sensor hardware and the weapon itself), increase the overall system complexity and would require additional design to incorporate into the stealth exterior.
2) Invest design dollars to reduce RF and IR signatures to minimize chance of detection and weapons lock.
3) Continue development on multi-spectrum jammers to divert the incoming missiles.
4) Increase the strike vehicle operational ceiling to allow more time for hostile missile detection and require more energy expenditure from the threat systems.

Consequence Mitigation

1) Build in redundant structures to support the air frame (adds to vehicle weight).

Scenario	Likelihood	Consequence
S15 - Control Surfaces (*Conventional*)	High	Serious

Likelihood Mitigation

1) Install on-board, active, anti-missile system (e.g., small laser to blind missile seeker hardware). This option will add extra weight (for the sensor hardware and the weapon itself), increase the overall system complexity and would require additional design to incorporate into the stealth exterior.
2) Reduce RF and IR signatures to minimize chance of detection and weapons lock

3) Continue development on multi-spectrum jammers to divert the incoming missiles.
4) Increase the strike vehicle operational ceiling to allow more time for hostile missile detection and require more energy expenditure from the threat systems.

Consequence Mitigation

1) Design robust control surfaces to allow for basic flight maneuvering even with heavy damage (will likely add to vehicle weight)
2) Design an inherently stable vehicle that requires minimal control surface input. While a more stable design would reduce maneuverability, this vehicle is not intended for air-to-air combat

Clearly there are multiple mitigation concepts available for each scenario, and they all require trade offs in design decisions and technology investment. Once all of the mitigation concepts have been laid out and quantified in terms of cost, schedule, and performance parameters it is possible to construct a decision tree that would allow the decision maker to focus on the most "bang-for-buck" research solutions.

4.4. Modeling a Decision Tool

In this research, it is clear additional technical data is required on each threat concept to make informed decisions. However, it is still possible to develop a decision tool for this problem using reasonable ranges for specific technical values and cost considerations. To demonstrate how the technique could be applied to analyze a decision maker's options, this research will develop a decision model to decide whether or not to invest in an onboard, anti-missile directed energy weapon (AMDEW)--since this type of system would be useful in countering many of the threat scenarios under consideration. This same process could be used for EMP hardening, adding redundant control structures, investing in "active stealth" research, etc.

Since this research focused on developing threat scenarios, not counter-threat systems, the decision model will rely on open source information, analogy, personal experience of the author and transparent, reasonable logic to establish quantitative ranges for evaluating an AMDEW. The values can be easily changed by decision makers to reflect more exact information or personal beliefs, and a sensitivity analysis will be performed to help determine which variables merit research toward greater accuracy.

To begin, it is useful to select existing systems that are analogous to the concept system under consideration in order to model the GSV parameters. Fortunately, a form of anti-missile directed energy weapon system is already in existence today. Northrop Grumman's "Nemesis" system is a directional infrared countermeasure (DIRCM) system currently being tested on commercial airlines in the United States. Realizing it is designed specifically for shoulder-fired, IR-seeker missiles and understanding that a DEW system on a strike vehicle would present a host of unique challenges in development, procurement and maintenance, the DIRCM system still provides the closest analogy to establish the basic decision model.

In developing the decision tree, it is necessary to create logical pathways that will include every significant decision point (see Figure 10). In this analysis, the first point decides whether or not to pursue the AMDEW system. Following the status quo route (no AMDEW) then takes us to the likelihood of an IADS launch. Considering that the strike vehicle would be flying a combat mission deep in enemy territory, and given that the GSV is detected, and given that the enemy possesses the advanced capability missile discussed in the threat scenario, it is likely that enemy forces would launch. So for the base case, this research will use a 0.90 probability situated between a 0.75 min and a 1.0 max.

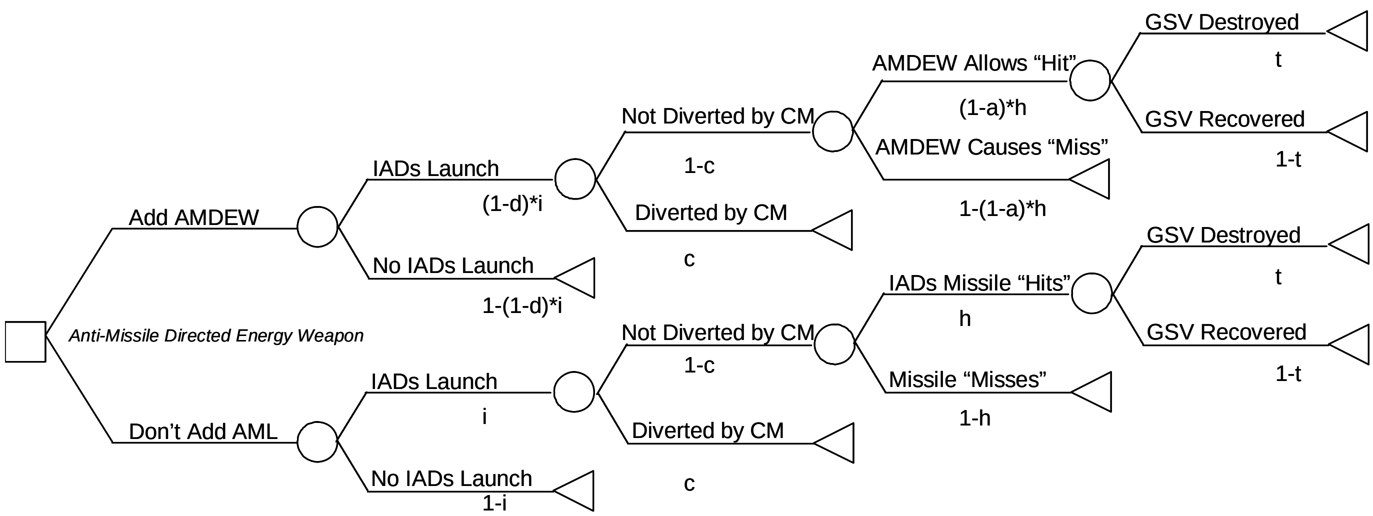

Figure 10: Model Decision Tree

Given that the launch does occur, the next juncture involves the suite of countermeasures employed today: Flares, Chaff, and ECM of various capabilities. These are exactly the types of countermeasures that would be penetrable by a multi-mode seeker missile with advance on-board processors as envisioned by the threat scenarios developed in Chapter 3. While there are certainly multiple technical specifications that would go into developing probabilities of this node, it may be just as effective to give a credible range. So for the base case the existing genre of countermeasures will be considered 30% effective in deflecting an advanced missile barrage. By setting the min at 15% and the max at 50% a good range of capability can be established (given the assumptions made about the threat).

Given that the conventional countermeasures fail to divert the missile(s) the next node posits the likelihood of a hit. Since failed countermeasures are effectively the same as no countermeasures, this hit probability assumes optimum conditions for the IADs missiles. Certainly there are other factors that could be considered (e.g., weather, look angle, etc.) but unimpeded missiles are pretty accurate in most conditions—even today—so the base case will be set at 0.8 to hit. The max will range up to 1.0 with the min being at least a .5 chance of hitting. It should also be noted that a "hit" does not necessarily indicate that the warhead physically struck the air vehicle. It could mean shrapnel from the warhead, overpressure damage from the explosion, or even EMP damage (depending on the warhead type). This distinction allows for multiple possibilities following a hit (depending on consequence mitigation), though our initial model will only consider two.

Given that the vehicle is "hit" there are two general possibilities that this model will consider: 1) The vehicle is effectively destroyed, or 2) the vehicle is able to retreat and is recovered by friendly forces. In either case this model assumes that a hit vehicle will result in mission failure. It is certainly possible to expand the model to include a "hit but still mission capable" option if consequence mitigation measures are included in the design assumptions along with associated probabilities of success.

Table 20: Decision Tree Variable Matrix

Probabilities	Min	Base	Max
i- enemy IADS launch when AF Strike Vehicle Detected	0.75	0.90	1.00
c - countermeasures (EW, Flair, Chaff, Sensors, etc.) engage and interdict advanced missile	0.15	0.30	0.50
h - hit (without any CM)	0.50	0.80	1.00
t - catastrophic consequences (resulting from a hit) that lead to loss of the GSV	0.70	0.80	0.90
Effectiveness	**Min**	**Base**	**Max**
d - deterrence effect on enemy launch decision	0.00	0.25	0.50
a - effectiveness of AMDEW (given that missile is detected and tracked)	0.75	0.90	1.00

The next phase of the analysis requires the creation of an estimate for the cost of developing and fielding the AMDEW system. This estimate will provide a measure by which to evaluate a trade between the competing values of cost and vehicle survivability. Open sources posit that it would cost about $10B to procure enough systems to outfit the 6,500 planes (1 system per plane) of the commercial passenger (and freight) industries with a DIRCM-like system. Additionally, estimates predict annual operations and maintenance costs of the integrated system would approach $2.5B (von Winterfeldt, 2006, and RAND, 2005). A simple, mathematical decomposition shows that the effective unit cost would be in the neighborhood of $1.5M (5.8M) per aircraft with an annual, per unit O&M cost of approximately $385K. R&D costs are not included in this estimate since it is not anticipated that the GSV program would not bear the weight of the development effort. Much of the R&D is ongoing today on similar systems, any future system would likely have its development costs amortized over a larger family of air vehicles.

Using a number of 100 global strike vehicles (GSV) gives an estimate of $150M ($1.5M x 100 vehicles) for system development, procurement, and deployment--and an estimate of $38.5M annually for fleet wide O&M of the system ($385M for the 10 year vehicle life). At first glance, these numbers may seem high (especially the O&M figures), but the analysis will allow for a range of values and provide a means to insert more accurate data as it becomes available.

For the unit cost of the strike vehicle, the best reference systems may be the F35 and F22 (once considered with a strike/bomber variant). Open source estimates place the unit cost of the F35 at around $30M, and the unit cost of the F22 at around $100M. Using those ranges as the upper and lower bound, the base case for the estimated GSV unit cost is established at the median value of $65M.

The crew size in modern, tactical-strike aircraft is typically one (e.g., F16, F117). But the crew size for a long-range, extended-duration, deep-strike aircraft is typically more than one (e.g., F111, B1, and B2), and it is also possible that the vehicle could be configured as an unmanned vehicle. For the base case, this research assumes two crew members. This consideration will become a factor when value of life is factored as part of the total economic equation.

In calculating the value of a human life there is no accepted answer, and any discussion is invariably fraught with emotional pleas and ambiguous criteria. However, considering the inherently dangerous nature of military combat operations, it is reasonable to approach the question from a more calculated, resource loss perspective. At the minimum, the military would likely consider each crew member to be worth the cost of his/her accession and training. So using a figure of $2.0 million to account for the recruiting, training and fielding of a pilot would seem to be a reasonable minimum value. At the opposite end of the spectrum, losing an experienced pilot (e.g., Lt Col) who has

20+ years of service represents a much greater investment in training and development, as well as a the value of experience, command potential, and (among other factors) the automatic survivors benefit plan payout (roughly equivalent to a $350K lump sum funding of an annuity for a Lt Col's survivors). So the high end is assumed to be $15M with $5 M for the base case.

For the cost of the mission weapons load this research assumes the vehicle is armed with a variant of today's Small Diameter Bomb (SDB) which is supposed to retail for under $40K. The base case is assumed to be 8 SDBs ($320K) and the range up to 12 ($480K) for the max and down to 6 ($240K) for the min.

The Value of the Mission must also be considered when calculating the impact of a vehicle loss. This number is certainly difficult to pin down—especially in terms of defining a dollar value to compare with other cost figures. To complicate the problem even more, every mission is different and the political, military and economic consequences may be far-reaching—especially considering that the GSV would be used to impart strategic level combat effects. Assuming that decision makers would like to maintain at least a 95% mission success rate one could say that a DM is willing to accept a 5% loss rate (Obviously, this number can vary based on the risk preferences of the DM: risk averse, risk neutral, or risk seeking). So at the very low end the value of the mission should at least be greater than 5% of the cost of the vehicle fleet and crew roster. This research constrains the high end to some number that explicitly impacts the decision maker in the Air Force. Considering that vehicle losses would likely impugn the reputation of the strike vehicle capabilities (e.g., F117 shot down by low tech air defenses) and even the entire global strike vehicle program—it may be reasonable to use some portion of the entire strike vehicle program cost as the value of the mission on the high end. Presumably, to precipitate a serious program impact, the vehicle failures must take place in operational strike vehicles fairly early in the production life. All of the R&D and initial procurement costs would have already been expended but the remaining production run of 50% of the 100 vehicle fleet could be at stake. So the high end mission value cost is the unit cost (low end estimate of $30M) of a GSV times 50 vehicles ($1.5B). The base case is assumed to be 50% of the max case ($750M).

Table 21: Expected Value of Consequences Matrix

Consequences		Min	Base	Max
VOL	Value of Life (Millions)	$2.00	$5.00	$15.00
FAT	Fatalities given loss of vehicle	1	2	2
CGSV	Cost of the GSV (Millions)	$30.00	$65.00	$100.00
CPAYLOAD	Cost of the Payload (Millions)	$0.24	$0.32	$0.48
CAMDEW	Cost of Antimissile System (Millions)	$100.00	$150.00	$200.00
VOM	Value of the Mission (Millions)	$160.00	$750.00	$1,500.00
CREPAIRS	Cost of Vehicle Repairs (Millions)	$0.50	$5.00	$10.00

Based on the values developed and outlined in Table 21, the expected cost for each termination node can be calculated using the following expected cost equations:

For a destroyed vehicle (Failed Mission):

$$EC = VOL*FAT+C_{GSV}+C_{PAYLOAD}+C_{AMDEW}+VOM$$

For a Recovered Vehicle (Failed Mission):

$$EC = C_{AMDEW}+C_{REPAIRS}+VOM$$

Using the probabilities and expected costs, the decision tree can be solved. Figure 11 shows a solved decision tree using the base case inputs. For the base case, one can see that although the projected cost of the AMDEW system is \$150M, the expected equivalent cost of employing the system (\$180.7M) is significantly less than the expected equivalent cost of not employing the system (\$408.7M).

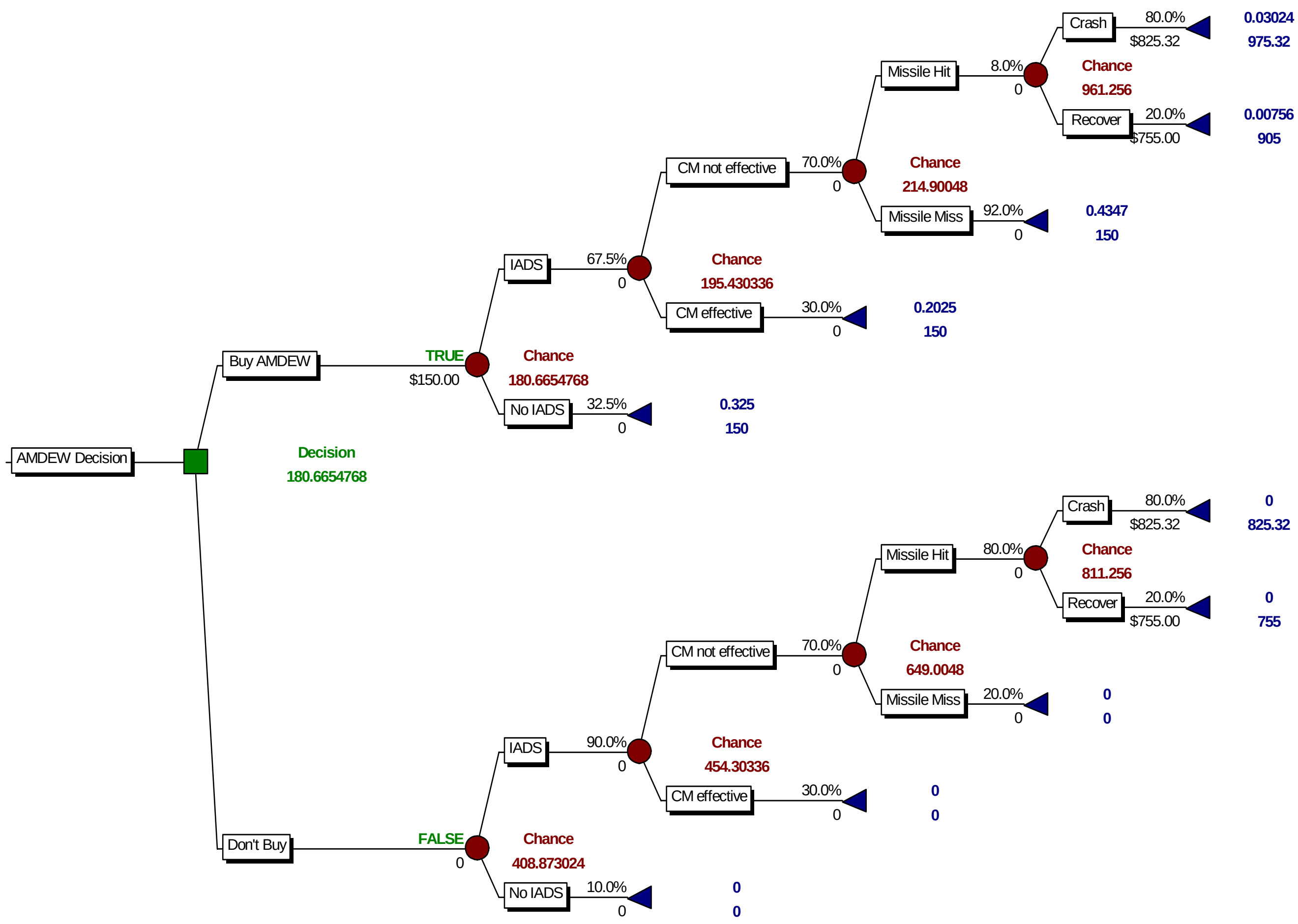

Figure 11: Solved Decision Tree

In order to ensure the decision maker's choice is clear, it is necessary to perform sensitivity analysis on all of the factors used in the decision. Given that the range of the decision inputs is appropriate, sensitivity analysis should illuminate those inputs that most affect the outcome. The complete analysis is displayed in Appendix A at the end of this document, but the tornado diagram (Figure 12) gives a fair overview of the effect each variable has on the decision. The most significant factors are clearly the Mission Value, AMDEW Effectiveness, Deterrence Effect, Probability of a Hit, the effectiveness of Countermeasures (not AMDEW), and the Probability of an IADs launch. All other factors, including the cost of the GSV, have no effect on the decision. The individual sensitivity analysis for each variable (Appendix A) paints an even clearer picture, as only one variable (Mission Value) affects the recommended decision (Figure 13). None of the other variables, when projected across the entire plausible range of values, drives the decision. This is particularly interesting since the ranges for each variable were specifically selected to represent a conservatively wide range of values. Based on the sensitivity analysis, there is really only one decision point. If the Mission Value is more than \$267M (\$483M less than the base case) then the AMDEW should not be purchased. Otherwise, it appears to be a good investment.

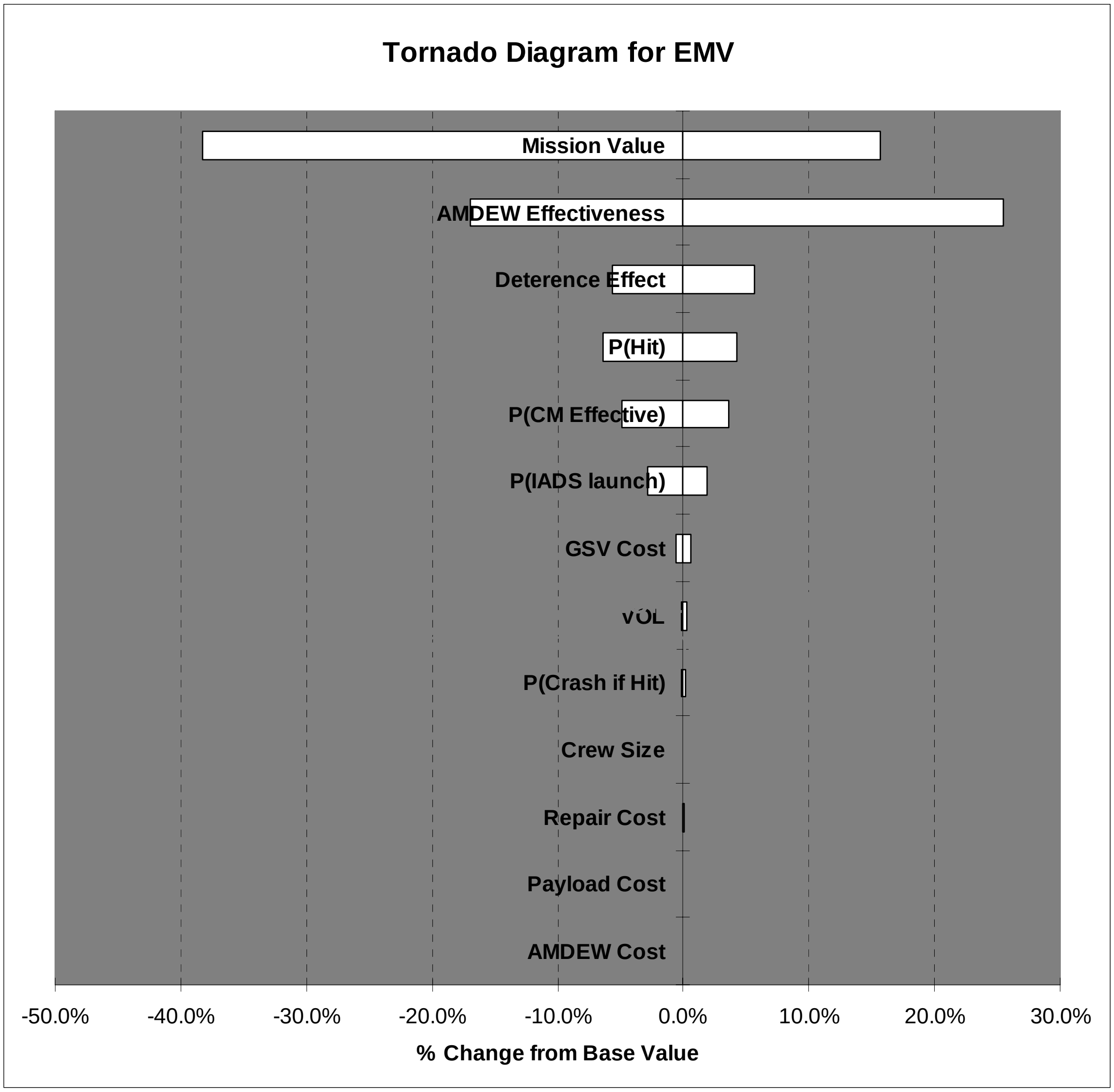

Figure 12: Tornado Diagram

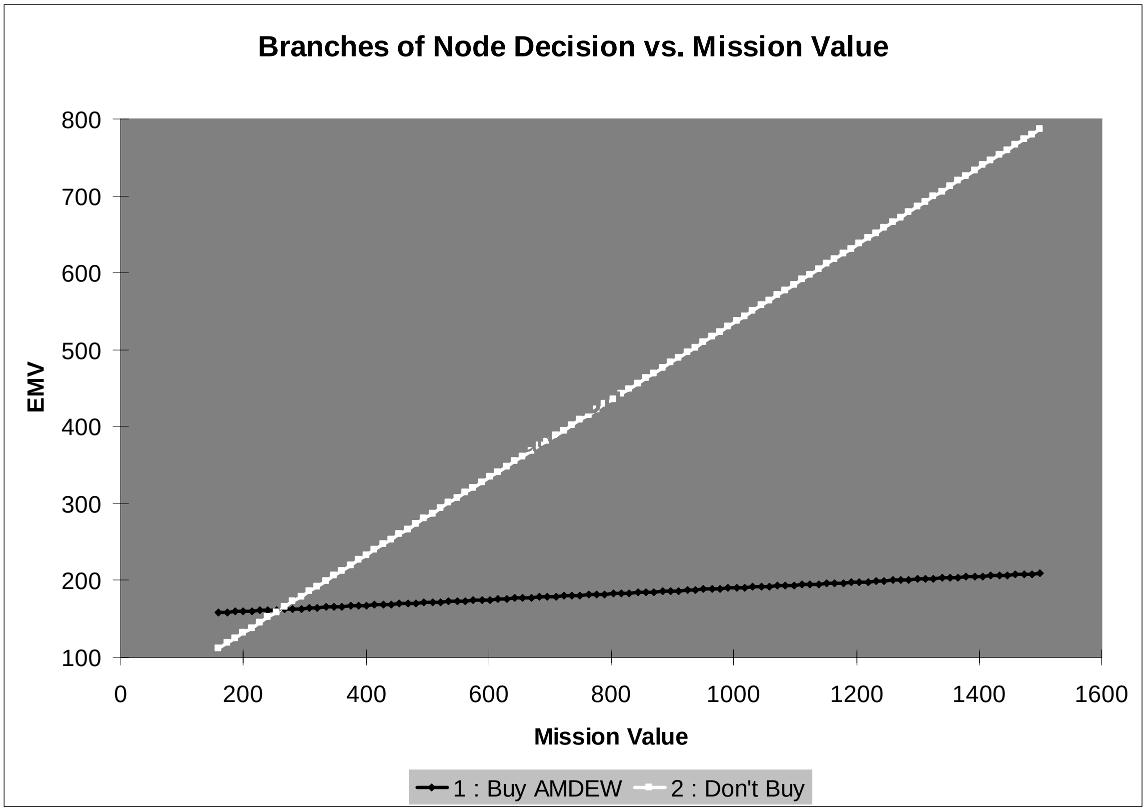

Figure 13: Sensitivity to Mission Value

To illuminate the decision further, it may be useful to view a risk profile (Figure 14) that visually displays the probability and severity for each consequence. Because of the relatively high probability of extreme consequences only the most risk seeking decision maker would choose to go without the AMDEW system.

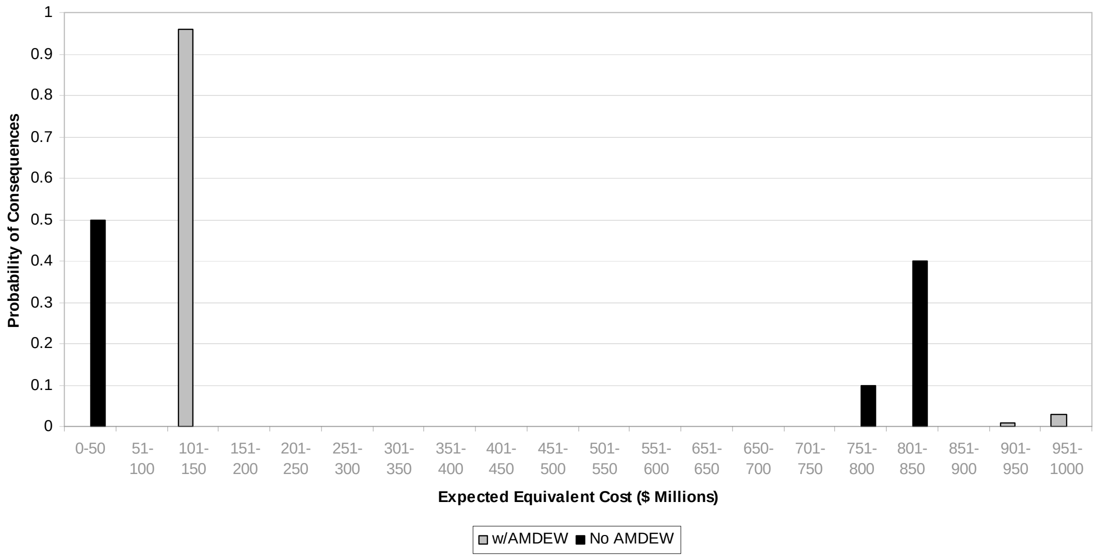

Figure 14: Consequence Probability vs. Expected Equivalent Cost

As a final check it is useful to conduct a two-way sensitivity analysis on the two most influential factors – Mission Value and AMDEW effectiveness. As expected, Figures 15 shows that the value of the mission is still the driving factor. However, a downshift in AMDEW effectiveness can move the decision point slightly—requiring a higher equivalent monetary value for the mission. The equation for the decision point is

$$Value\ of\ Mission \geq \frac{\left[142.3 - 23.2\left(AMDEW\ effectiveness\right)\right]}{\left[0.1 - 0.4\left(AMDEW\ effectiveness\right)\right]}$$

If the equation above is satisfied then the AMDEW is a good investment.

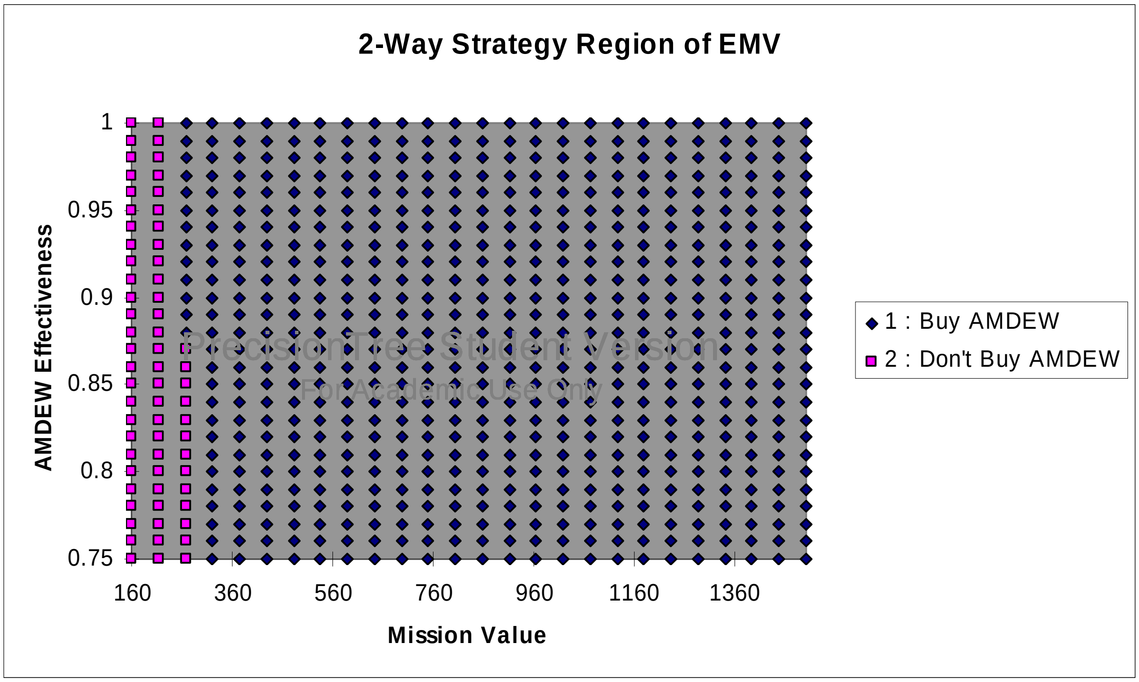

Figure 15: Two-Way Analysis of Mission Value and AMDEW Effectiveness

By choosing a technology that affects the likelihood of multiple scenarios the risk conscious decision maker can significantly shift the risk portfolio toward the left. To examine the aggregate impact of employing an effective AMDEW system, the risk matrix could be modified to show the shift across several scenarios (Table 22). While it may not necessarily shift the likelihood to a less severe category, it is clear (in the case of the AMDEW system) that movement occurs in a positive direction in 50% of the threat scenarios.

By making additional adjustments in the way of consequence mitigation (e.g., EMP hardening), the decision maker could also potentially reduce the expected consequences and shift the scenario in to a less severe outcome category. This type of shift analysis could be useful in helping determine which mix of likelihood/consequence mitigation measures provides the most impact for the least effort—though cost is not explicitly displayed.

Table 22: Modified Risk Matrix

	Very Low	Low	Moderate	High	Very High
Catastrophic		S12	**S13new**	S1 S13 S23	
Critical	**S11new**	S11	**S14new**	S10 S14	
Serious			**S15new**	S15	
Moderate					
Marginal					

In a similar way, a more complex decision tree could be constructed to account for more than one variable. The advantage being that the, decision maker could consider expected equivalent costs at the same time he is considering different mitigation measures. To illustrate the concept, the consequence mitigation measure "EMP Hardening" can be added to the analysis. This requires the additional variables of "EMP Hardening Effectiveness" and "EMP Hardening Cost." The effectiveness will range from 10% to 80%, with 60% as the base case. The cost will range from 10% of the GSV unit cost to 50% of the GSV cost, with 25% as the base case.

Figures 16 and 17 below show the likelihood mitigation measure of an AMDEW system being considered as well as the consequence mitigation measure of EMP

Hardening. Somewhat surprisingly, the EMV calculation still favors the AMDEW-only approach, and centers on Mission Value as the most influential factor.

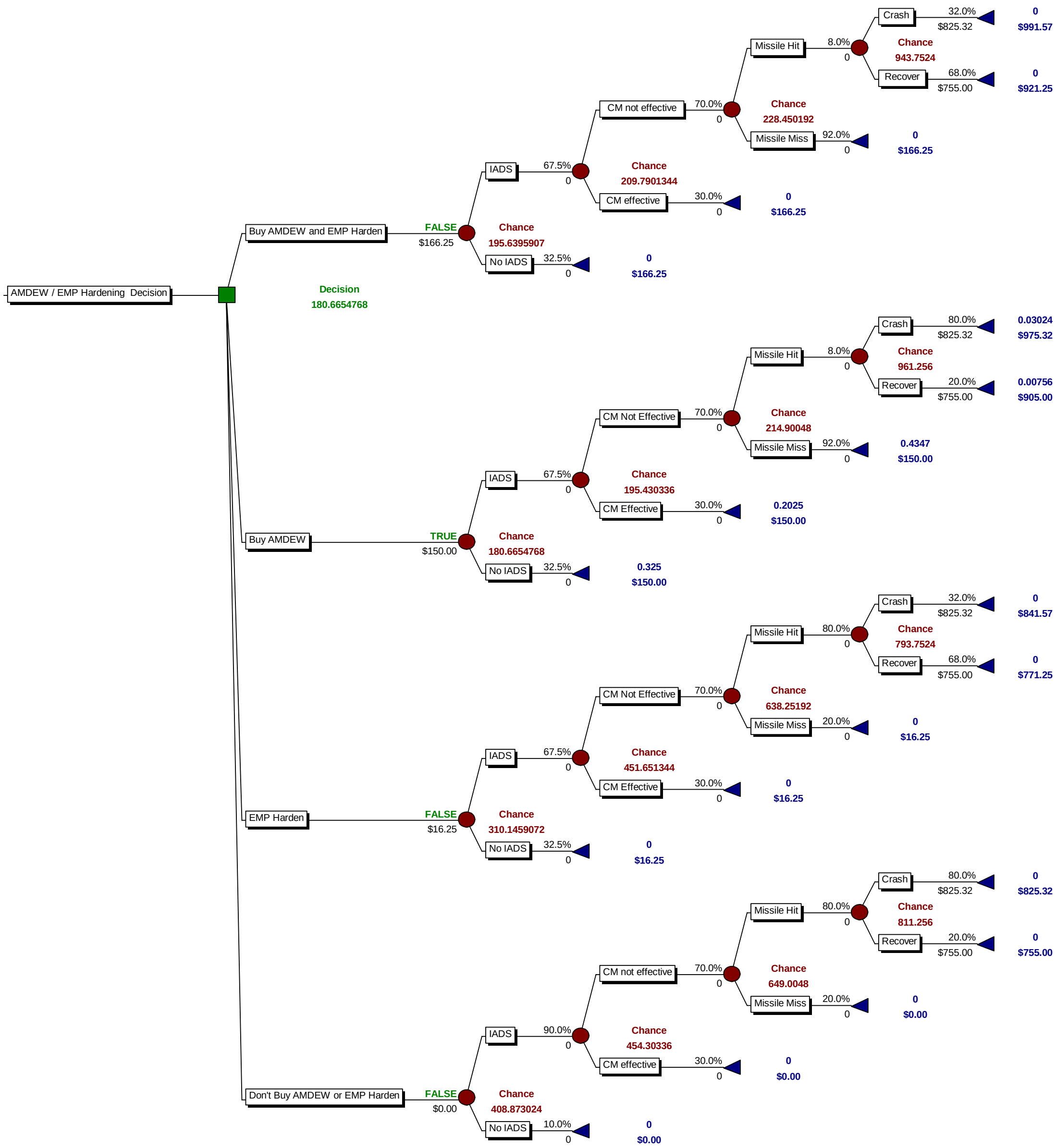

Figure 16: Multi-Criteria Decision Tree

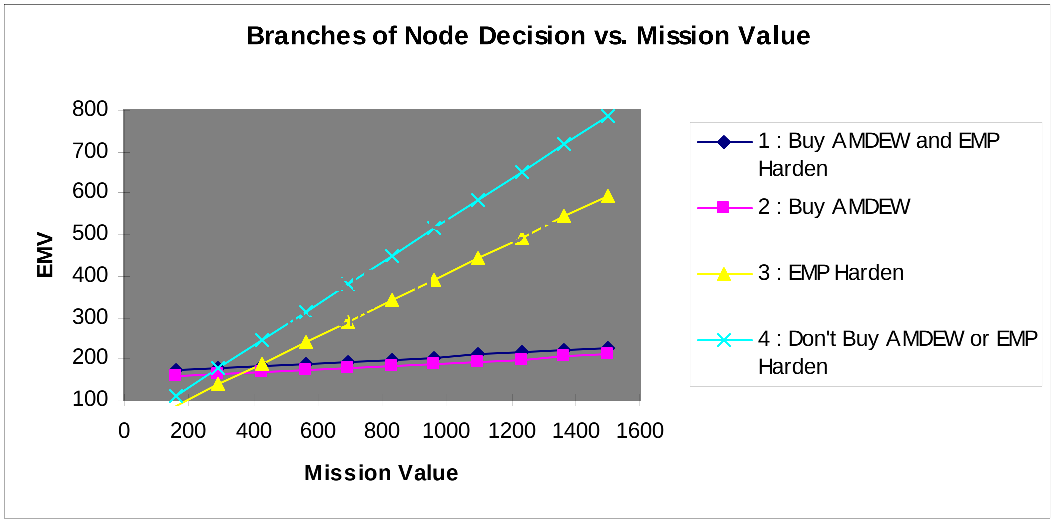

Figure 17: Sensitivity to Mission Value

4.5. Summary

Working on "future prediction" projects is inherently a struggle with uncertainty. Even the most experienced planners, futurist and subject matter experts will likely present wide-ranging opinions on most topics of interest. The challenge to R&D organizations is to bracket the future with a wide enough margin to include all plausible scenarios, but not so wide as to entertain ambiguity. This analysis has demonstrated that relatively straight-forward techniques (Decision Trees, and Sensitivity Analysis) can be useful in focusing the decision makers on the elements that matter most to future weapon systems.

5. Conclusions

The purpose of this research was to help generate useful threat scenarios to aid decision makers in planning for the defensive systems of the Global Strike Vehicle that will operate through 2035. It should be clearly noted that this research product was designed as an example of one process to achieve those aims. It is not a technical report on advanced technologies, nor is it intended to be a definitive prediction of future technologies or the world geopolitical situation. Those goals are well beyond the scope of this effort. Instead this research employed credible processes (Risk Filtering Ranking and Management, Decision Trees, and Sensitivity Analysis) to evaluate possible scenarios, which were generated through a reasonable synthesis of credible, relevant future studies and technology assessments conducted by recognized experts and professionals in their fields. Additionally, all of the reports and data used in this research are explicitly from open sources. Therefore, it is reasonable to assume that the decision makers for any future Air Force development project would still need to access the most current, detailed, classified information on threat systems available. Such information could easily be used to add scenarios, modify the likelihood and consequence ratings of specific scenarios, adjust the cost ranges, and generally provide a greater degree of confidence in the final result. Employing actual parameters of current weapon systems (operational-based data and cost-based data) may also allow planners to predict thresholds at which emerging technologies would compromise current systems.

5.1. Recommendations for Strike System Planners

The RFRM method seems to be an excellent approach for exploring and organizing threats to Air Force assets. While it is true that the data used in this study were open source and, perhaps, not detailed enough for making binding program decisions, it is also true that it has generated some reasonable starting points for more detailed exploration. Of particular note is the concept of non-nuclear Electomagnetic Pulse (EMP) weapons that could derail a strike mission without relying on the precise targeting capabilities required by directed energy and kinetic weapons. The potential for probable adversaries to reduce the effectiveness of today's stealth technologies also seems highly likely. While pinpoint tracking and targeting of stealth vehicles may not be realized, it may not be necessary for enemy systems to be that good. Simple detection of a hostile (U.S.) air vehicle in the defender's air space may give enough information to partially damage or disable the vehicle and make it vulnerable to less advanced, but still effective aircraft kill systems.

At the very least, the approaches explored in this research should provide decision makers with a method for incorporating formal studies, Red Team exercises and additional research into a coherent decision structure that can be evaluated and adjusted over time.

5.2. Recommendations for Future Research

This research, while useful as a foundation (or at least as a methodology template) requires much greater technical granularity to enable a true quantitative analysis that could lead to program-level design decisions. That level of detail will undoubtedly require access to classified data and classified expert assessments to attain operational quality decision making. Additional research would also be appropriate (as separate projects) to develop more detailed capabilities projections on each of the three major threat areas of EMP, Directed Energy Weapons (DEW), and Advanced Detection Systems. Additional research also seems needed in the area of quantifying the value of a strike mission so that it can be properly considered in any risk management plan.

5.3. Final Summary

The goal of this research was to add to the body of knowledge. It clearly demonstrated the utility of the RFRM process as a useful tool for developing risk scenarios. It demonstrated that using existing studies and open source technical evaluations can be useful in establishing a general threat framework. And it showed how employing future studies in concert with technology projections in a transparent process can help constrain an open-ended, speculative design question to a framework of reasonable propositions and rational operational scenarios to help guide the systems engineering effort.

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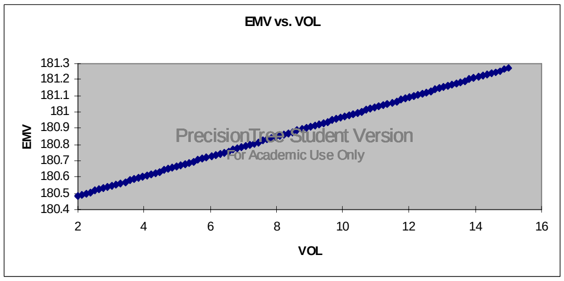
Appendix A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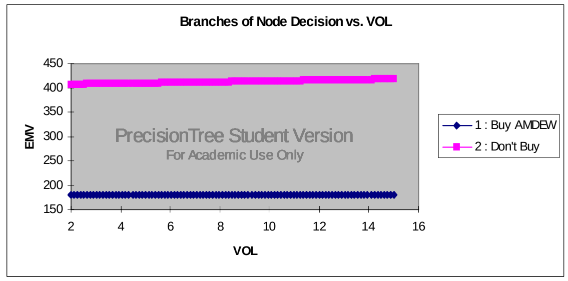
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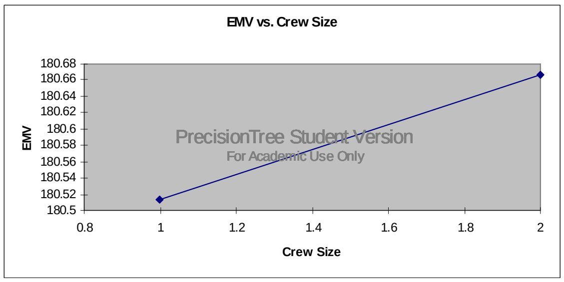
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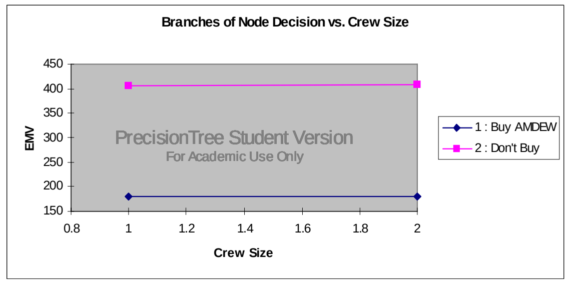
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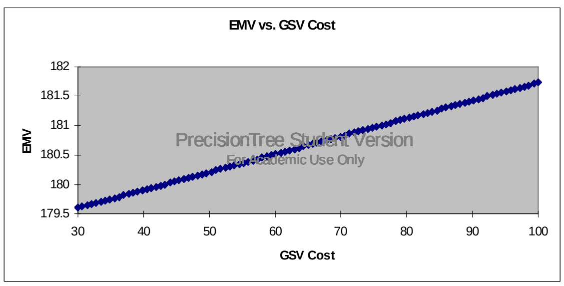
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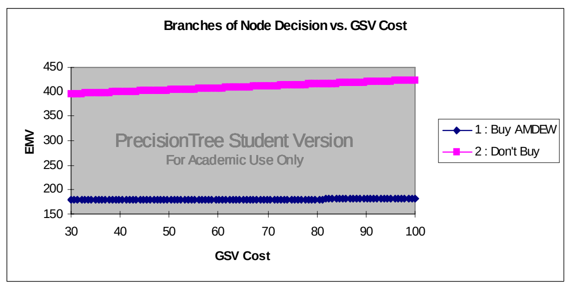
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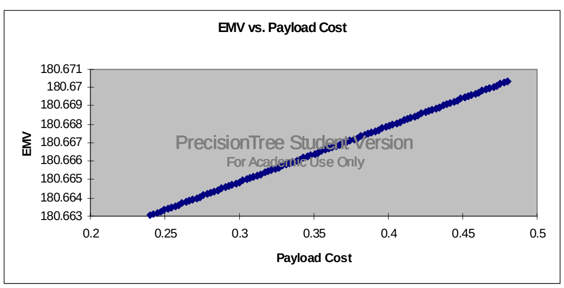
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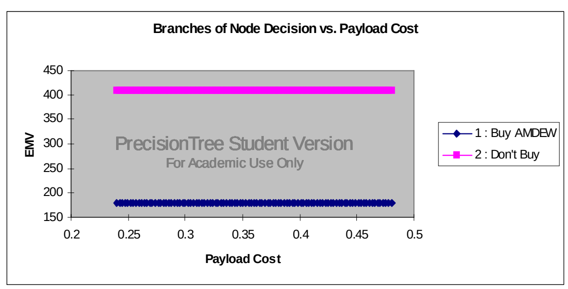
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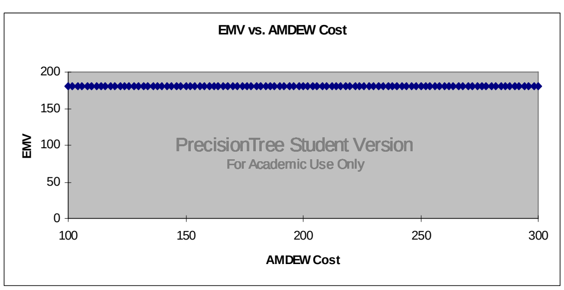
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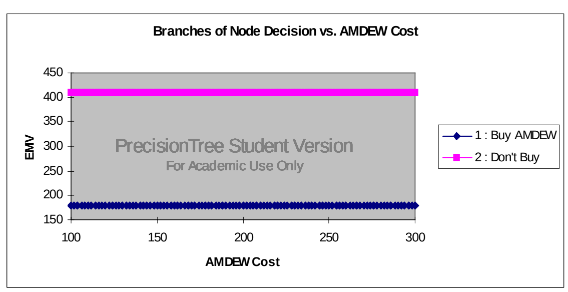
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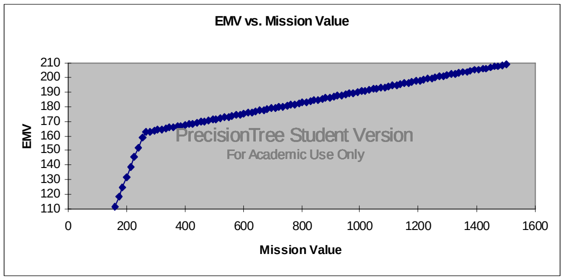
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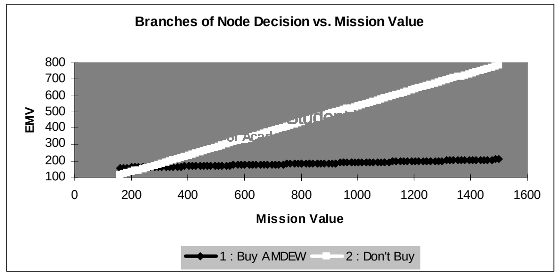
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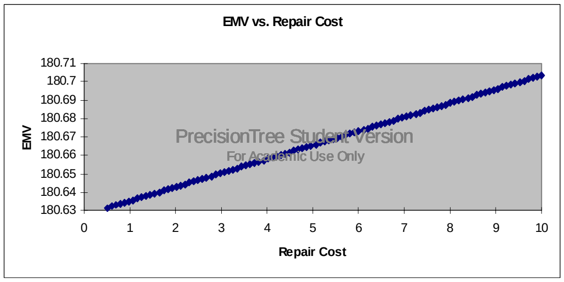
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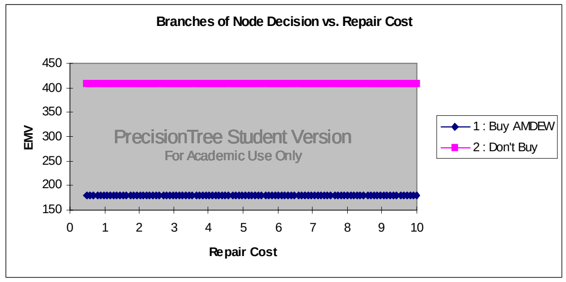
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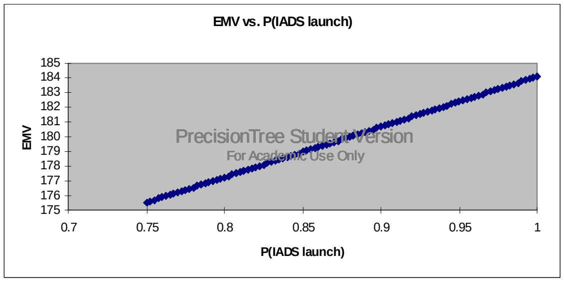
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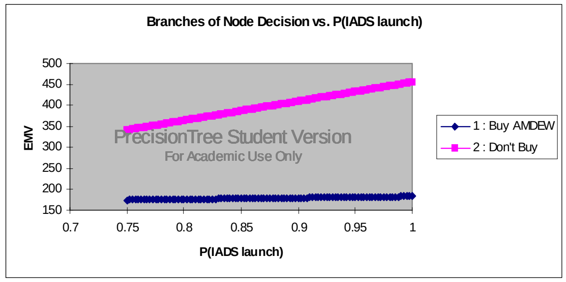
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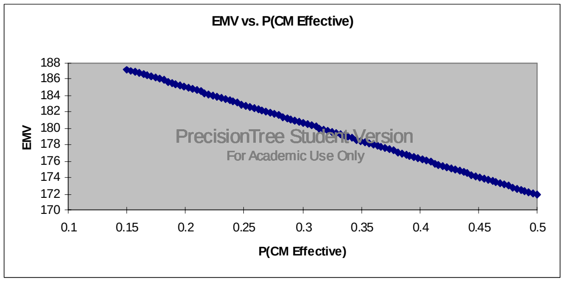
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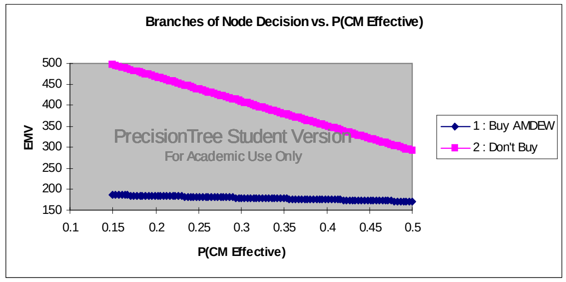
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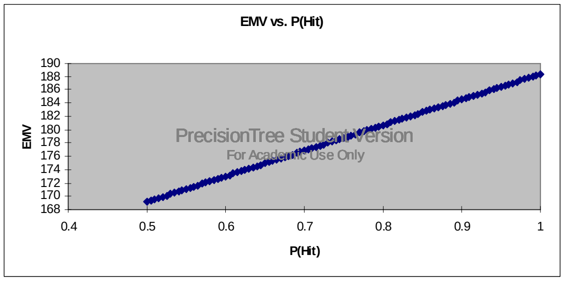
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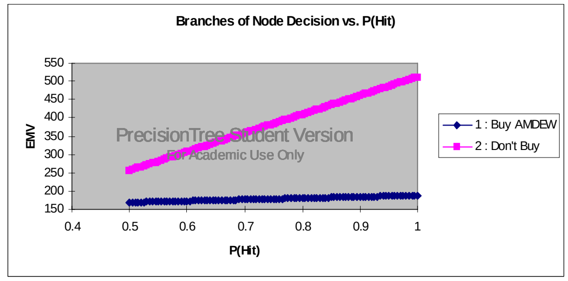
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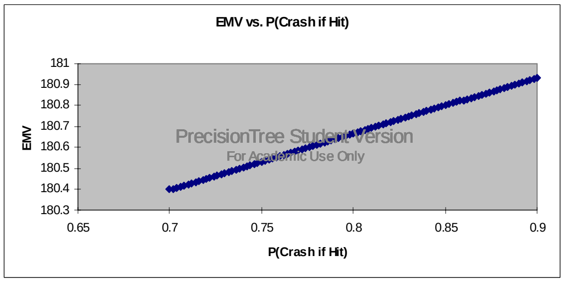
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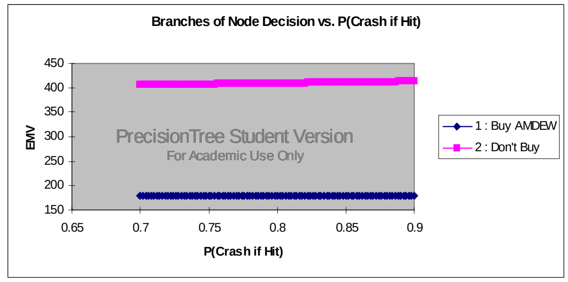
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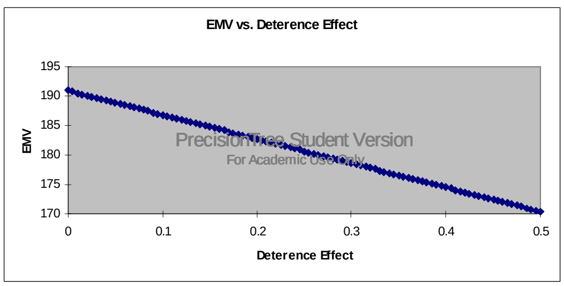
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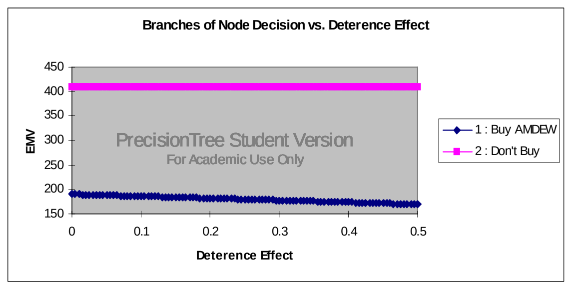
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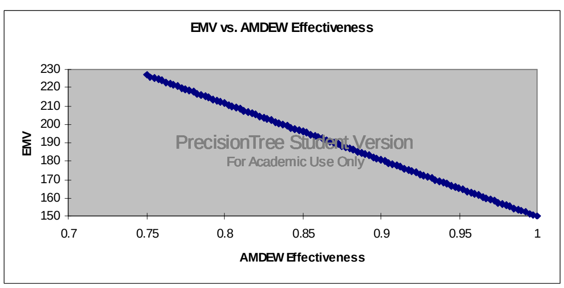
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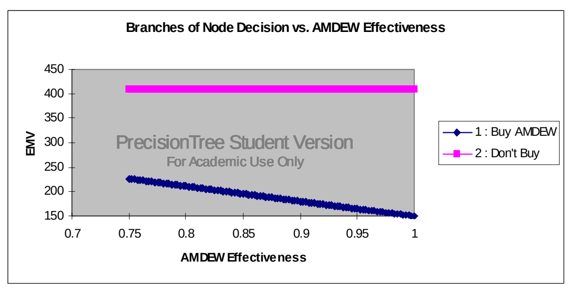
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6. AUTHOR(S) Heuck, William D., Jr., Major, USAF			**5d. PROJECT NUMBER** **5e. TASK NUMBER** **5f. WORK UNIT NUMBER**
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14. ABSTRACT

The United States Air Force today faces the challenge of allocating development resources to prepare for future force projection requirements. In particular, the Air Force's core competency of Global Attack implies a future capability that can quickly and successfully deliver combat effects anywhere in the world with impunity. Understanding that the future threat environment is dynamic and that continued advancements by adversaries will likely degrade the technical superiority of today's weapon systems, the need arises for a planning model to direct development funding to areas with the greatest probability of successfully defending the strike vehicle of 2035. Examining this problem posed two distinct challenges. The first was to determine the most likely course of Integrated Air Defense System technology through the time period of interest--allowing for plausible disruptive technologies that generate orders-of-magnitude improvement in capability or even change the nature of air defense systems. The second challenge was to characterize future adversaries--requiring a broad look at political and economic trends as presented in *AF 2025*, *SPACECAST 2020* and other relevant future studies. Based on these studies, threat scenarios were generated from technical assessments of emerging technologies and evaluated using the Risk Filtering, Ranking and Management (RFRM) technique (Haimes, 2004) to explore the most severe threats to a future global strike air vehicle. The application of RFRM to the problem created a coherent threat hierarchy that enables the decision maker to examine anticipated hostile systems that may counter key U.S. strengths of stealth, speed, and high altitude operations. Those threat scenarios were then evaluated using decision trees and sensitivity analysis to demonstrate how quantitative tools can be applied to a largely qualitative problem. Finally, this research produced an unclassified model of plausible scenarios and a variable analysis tool that is useful today, but could also be enhanced by the application of current intelligence data and updated technology projections in the future.

15. SUBJECT TERMS

Risk Filtering Ranking and Management (RFRM), Alternative Futures, Future Technologies, Threat Scenarios

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** Gary W. Kinney, Major, USAF (ENS)
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